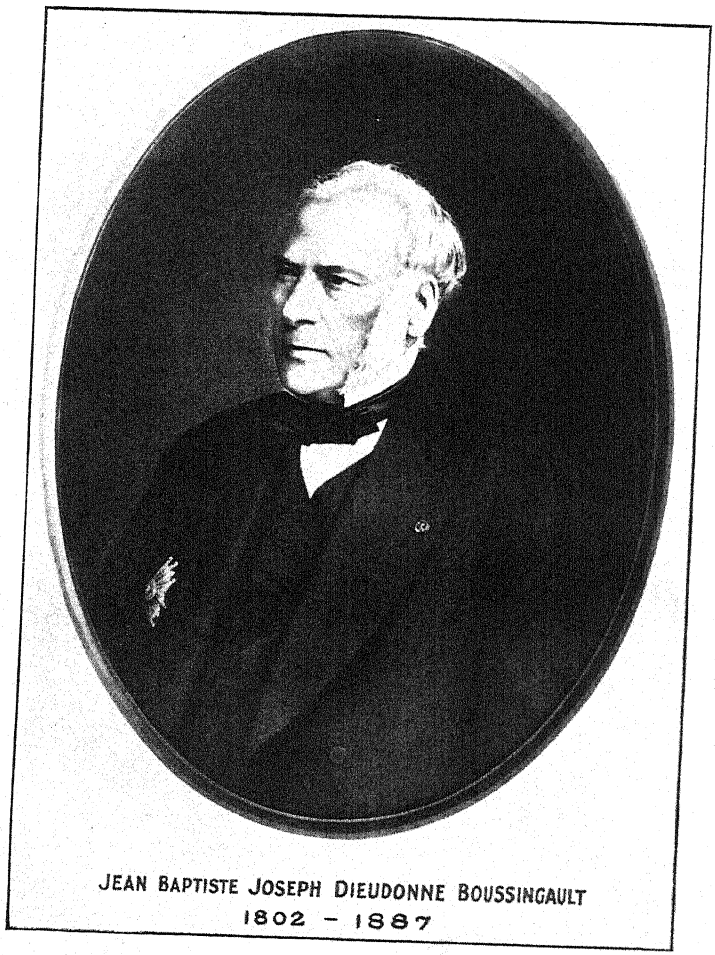

The Founder of Modern Agricultural Chemistry.

SOIL CONDITIONS
AND
PLANT GROWTH

BY

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WITH ILLUSTRATIONS

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PREFACE TO THE SEVENTH EDITION.

ONCE again a new edition is required, and again I have been fortunate in the time.

During the last three years I have visited many of the Agricultural Experiment Stations in Europe, including Poland and Russia—not yet, however, all that I wish to visit—and discussed problems and results with the various workers in their own laboratories. In 1935 also the International Society of Soil Science held its Third Congress at Oxford, and did me the honour of making me President. Most of the leading soil investigators of the world were there, and in the numerous papers and discussions practically the whole ground of Soil Science was covered.

In these various ways I have accumulated a considerable amount of material, and I have selected from it whatever seemed suitable for the present edition. The changes are so considerable that much of the book has had to be rewritten.

Its purpose, however, remains unaltered: it is to present the student with the broad outlines of the subject, including sufficient detail to give reality to the treatment but avoiding always the tediousness of the card-index record. The numerous references have been so selected that they at once lead the student into the literature of the particular problem. Additional space was of course needed for the new material, but I have been able to reduce in other directions so as to avoid increasing the size of the

book: I do not wish it to grow too large; it is intended to be read, not merely consulted like a dictionary.

Space has been saved by omitting the Appendix of Analytical Methods: instead there is a short list of easily obtainable books and papers containing the details necessary for laboratory work. I have also curtailed the Bibliography. The papers on the subject have multiplied at such a rate that no Appendix could possibly keep pace with them: and the difficulty is increased by the growing tendency to disperse results over a number of widely scattered papers instead of concentrating them in one good memoir. Fortunately the difficulty has been solved: the Imperial Bureau of Soil Science, Rothamsted Experimental Station, has issued a Bibliography which includes all recent papers.

As in the earlier editions, I have been greatly helped by my colleagues at Rothamsted: in Chapter II by Mr. F. J. Richards and Dr. D. J. Watson; Chapters III, IV, VII and VIII have been drastically overhauled by Dr. E. W. Russell; and much assistance has been rendered by Drs. H. L. Richardson, R. K. Schofield and E. M. Crowther: in Chapters V and VI Miss L. M. Crump and Dr. H. Nicol have given considerable help. To all these I can only very inadequately express my thanks; the book has continued to live because of the labour so generously devoted to it.

E. J. RUSSELL.

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When an author's name is followed by a date thus: Boyle (1661), the reader will find the full reference in the Bibliography, pp. 603 *et seq.*

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CHAPTER I.

HISTORICAL AND INTRODUCTORY.

In all ages the growth of plants has interested thoughtful men. The mystery of the change of an apparently lifeless seed to a vigorous growing plant never loses its freshness, and constitutes, indeed, no small part of the charm of gardening. The economic problems are of vital importance, and become more and more urgent as time goes on and populations increase and their needs become more complex.

There was an extensive literature on agriculture in Roman times which maintained a pre-eminent position until comparatively recently. In this we find collected many of the facts which it has subsequently been the business of agricultural experts to classify and explain. The Roman literature was collected and condensed into one volume about the year 1240 by a senator of Bologna, Petrus Crescentius, whose book [1] was one of the most popular treatises on agriculture of any time, being frequently copied, and in the early days of printing, passing through many editions—some of them very handsome, and ultimately giving rise to the large standard European treatises of the sixteenth and seventeenth centuries. Many other agricultural books appeared in the fifteenth and early sixteenth centuries, notably in Italy, and later in France. In some of these are found certain ingenious speculations that have been justified by later work. Such, for instance, is Palissy's remarkable statement in 1563: "You will admit that when you bring dung into the field it is to return to the soil something that has been taken away. . . . When a plant

[1] *De agricultura vulgare*, Augsburg, 1471, and many subsequent editions.

is burned it is reduced to a salty ash called alcaly by apothecaries and philosophers. . . . Every sort of plant without exception contains some kind of salt. Have you not seen certain labourers when sowing a field with wheat for the second year in succession, burn the unused wheat straw which had been taken from the field? In the ashes will be found the salt that the straw took out of the soil; if this is put back the soil is improved. Being burnt on the ground it serves as manure because it returns to the soil those substances that had been taken away." But for every speculation that has been confirmed will be found many that have not, and the beginnings of agricultural chemistry must be sought later, when men had learnt the necessity for carrying on experiments.

The Search for the "Principle" of Vegetation, 1630-1750.

The earlier investigators sought for a "principle" of vegetation to account for the phenomena of soil fertility and plant growth. The great Francis Bacon, Lord Verulam (1627), believed that water formed the "principal nourishment" of plants, the purpose of the soil being to keep them upright and protect them from excessive cold or heat, but he also considered that each plant drew a "particular juyce" from the soil for its sustenance, thereby impoverishing the soil for that particular plant and similar ones, but not necessarily for other plants. Van Helmont regarded water as the sole nutrient for plants, and his son thus records his famous Brussels experiment (1577-1644): "I took an earthen vessel in which I put 200 pounds of soil dried in an oven, then I moistened with rain water and pressed hard into it a shoot of willow weighing 5 pounds. After exactly five years the tree that had grown up weighed 169 pounds and about three ounces. But the vessel had never received anything but rain water or distilled water to moisten the soil when this was necessary, and it remained full of soil, which was still tightly packed, and, lest any dust from outside should get into the soil, it was covered

with a sheet of iron coated with tin but perforated with many holes. I did not take the weight of the leaves that fell in the autumn. In the end I dried the soil once more and got the same 200 pounds that I started with, less about two ounces. Therefore the 164 pounds of wood, bark, and root arose from the water alone."

The experiment is simple and convincing, and satisfied Boyle (1661), who repeated it with "squash, a kind of Indian pompion" and obtained similar results. Boyle further distilled the plants and concluded, quite justifiably from his premises, that the products obtained, "salt, spirit, earth, and even oil (though that be thought of all bodies the most opposite to water), may be produced out of water." Nevertheless, the conclusion is incorrect, because two factors had escaped Van Helmont's notice—the parts played by the air and by the missing two ounces of soil. But the history of this experiment is thoroughly typical of experiments in agricultural chemistry generally: in no other subject is it so easy to overlook a vital factor and draw from good experiments a conclusion that appears to be absolutely sound, but is in reality entirely wrong.

Some years later (1656) Glauber set up the hypothesis that saltpetre is the "principle" of vegetation. Having obtained saltpetre from the earth cleared out from cattle sheds, he argued that it must have come from the urine or droppings of the animals, and must, therefore, be contained in the animal's food, *i.e.* in plants. He also found that additions of saltpetre to the soil produced enormous increases in crop. He connected these two observations and supposed that saltpetre is the essential principle of vegetation. The fertility of the soil and the value of manures (he mentions dung, feathers, hair, horn, bones, cloth cuttings) are entirely due to saltpetre.

This view was supported by Mayow's experiments (1674). He estimated the amounts of nitre in the soil at different times of the year, and showed that it occurs in greatest quantity in

spring when plants are just beginning to grow, but is not to be found " in soil on which plants grow abundantly, the reason being that all the nitre of the soil is sucked out by the plants." J. A. Külbel,[1] on the other hand, regarded a *magma unguinosum* obtainable from humus as the " principle " sought for.

The most accurate work in this period was published by John Woodward (1699) in a remarkable paper. Setting out from the experiments of Van Helmont and of Boyle, but apparently knowing nothing of the work of Glauber and of Mayow, he grew spearmint in water obtained from various sources with the following results among others :—

Source of Water.	Weight of Plants.		Gained in 77 days.	Expense of Water (*i.e.* Transpiration).	Proportion of Increase of Plant to Expense of Water.
	When put in.	When taken out.			
	Grains.	Grains.	Grains.	Grains.	
Rain water . .	28¼	45¾	17½	3004	1 to 171$\frac{33}{35}$
River Thames . .	28	54	26	2493	1 to 95$\frac{83}{120}$
Hyde Park conduit .	110	249	139	131140	1 to 94$\frac{74}{1880}$
" " + 1½ oz. garden mould	92	376	284	14950	1 to 52$\frac{180}{284}$

Now all these plants had abundance of water, therefore all should have made equal growth had nothing more been needed. The amount of growth, however, increased with the impurity of the water. " Vegetables," he concludes, " are not formed of water, but of a certain peculiar terrestrial matter. It has been shown that there is a considerable quantity of this matter contained in rain, spring, and river water, that the greatest part of the fluid mass that ascends up into plants does not settle there but passes through their pores and exhales up into the atmosphere : that a great part of the terrestrial matter, mixed with the water, passes up into the plant along with it, and that the plant is more or less augmented in proportion as

[1] *Cause de la fertilité des terres,* Bordeaux, 1741.

the water contains a greater or less quantity of that matter; from all of which we may reasonably infer, that earth, and not water, is the matter that constitutes vegetables."

He discusses the use of manures and the fertility of the soil from this point of view, attributing the well-known falling off in crop yield when plants are grown for successive years on unmanured land to the circumstance that "the vegetable matter that it at first abounded in being extracted from it by those successive crops, is most of it borne off. . . . The land may be brought to produce another series of the same vegetables, but not until it is supplied with a new fund of matter, of like sort with that it at first contained; which supply is made several ways, either by the ground's being fallow some time, until the rain has poured down a fresh stock upon it; or by the tiller's care in manuring it." The best manures, he continues, are parts either of vegetables or of animals, which ultimately are derived from vegetables.

In his celebrated textbook of chemistry, Boerhaave (1727) taught that plants absorb the juices of the earth and then work them up into food. The raw material, the "prime radical juice of vegetables, is a compound from all the three kingdoms, *viz. fossil* bodies and putrified parts of *animals* and *vegetables*." This "we look upon as the *chyle of the plant;* being chiefly found in the first order of vessels, *viz.* in the roots and the body of the plant, which answers to the stomach and intestines of an animal."

For many years no such outstanding work as that of Glauber and Woodward was published, if we except Hales' *Vegetable Staticks* (1731), the interest of which is physiological rather than agricultural.[1] Advances were, however, being made in agricultural practice. One of the most important was the introduction of the drill and the horse hoe by Jethro Tull (1731), an Oxford man of a strongly practical turn of mind, who insisted on the vital importance of getting the soil

[1] He shows, however, that air is "wrought into the composition" of plants.

into a fine crumbly state for plant growth. Tull was more than an inventor; he discussed in most picturesque language the sources of fertility in the soil. In his view it was not the juices of the earth, but the very minute particles of soil loosened by the action of moisture, that constituted the "proper pabulum" of plants. The pressure caused by the swelling of the growing roots forced these particles into the "lacteal mouths of the roots," where they entered the circulatory system. All plants lived on these particles, *i.e.* on the same kind of food; it was incorrect to assert, as some had done, that different kinds of plants fed as differently as horses and dogs, each taking its appropriate food and no other. Plants will take in anything that comes their way, good or bad. A rotation of crops is not a necessity, but only a convenience. Conversely, any soil will nourish any plant if the temperature and water supply are properly regulated. Hoeing increased the surface of the soil or the "pasture of the plant," and also enabled the soil better to absorb the nutritious vapours condensed from the air. Dung acted in the same way, but was more costly and less efficient.

So much were Tull's writings esteemed, Cobbett tells us, that they were "plundered by English writers not a few and by Scotch in whole banditti."

The position at the end of this period cannot better be summed up than in Tull's own words: "It is agreed that all the following materials contribute in some manner to the increase of plants, but it is disputed which of them is that very increase or food: (1) nitre, (2) water, (3) air, (4) fire, (5) earth."

The Search for Plant Nutrients.

1. *The Phlogistic Period*, 1750-1800.

Great interest was taken in agriculture in this country during the latter half of the eighteenth century. "The

farming tribe," writes Arthur Young during this period, "is now made up of all ranks, from a duke to an apprentice." Many experiments were conducted, facts were accumulated, books written, and societies formed for promoting agriculture. The Edinburgh Society, established in 1755 for the improvement of arts and manufactures, induced Francis Home (1757) "to try how far chymistry will go in settling the principles of agriculture." The whole art of agriculture, he says, centres in one point: the nourishing of plants. Investigation of fertile soils showed that they contain oil, which is therefore a food of plants. But when a soil has been exhausted by cropping, it recovers its fertility on exposure to air,[1] which therefore supplies another food. Home made pot experiments to ascertain the effect of various substances on plant growth. "The more they (*i.e.* farmers) know of the effects of different bodies on plants, the greater chance they have to discover the nourishment of plants, at least this is the only road." Saltpetre, Epsom salt, vitriolated tartar (*i.e.* potassium sulphate) all lead to increased plant growth, yet they are three distinct salts. Olive oil was also useful. It is thus clear that plant food is not one thing only, but several; he enumerates six: air, water, earth, salts of different kinds, oil, and fire in a fixed state. As further proof he shows that "all vegetables and vegetable juices afford those very principles, and no other, by all the chymical experiments which have yet been made on them with or without fire."

The book is a great advance on anything that had gone before it, not only because it recognises that plant nutrition depends on several factors, but because it indicates so clearly the two methods to be followed in studying the problem—pot cultures and plant analysis. Subsequent investigators, Wallerius (1761), the Earl of Dundonald (1795), and Kirwan (1796) added new details but no new principles. The problem, indeed, was carried as far as was possible until further advances were made in plant physiology and in chemistry. The writers just

[1] Recorded by most early writers, *e.g.* Evelyn (*Terra*, 1674).

mentioned are, however, too important to be passed over completely. Wallerius, in 1761, professor of chemistry at Upsala, after analysing plants to discover the materials on which they live, and arguing that *Nutritio non fieri potest a rebus heterogeneis, sed homogeneis*, concludes that humus, being *homogeneous*, is the source of their food—the *nutritiva*—while the other soil constituents are *instrumentalia*, making the proper food mixture, dissolving and attenuating it, till it can enter the plant root. Thus chalk and probably salts help in dissolving the "fatness" of the humus. Clay helps to retain the "fatness" and prevent it being washed away by rain: sand keeps the soil open and pervious to air. The Earl of Dundonald, in 1795, adds alkaline phosphates to the list of nutritive salts, but he attaches chief importance to humus as plant food. The "oxygenation" process going on in the soil makes the organic matter insoluble and therefore useless for the plant; lime, "alkalis and other saline substances" dissolve it and change it to plant food; hence these substances should be used alternately with dung as manure. Manures were thus divided, as by Wallerius, into two classes: those that afford plant food, and those that have some indirect effect.

Throughout this period it was believed that plants could generate alkalis. "Alkalis," wrote Kirwan in 1796, "seem to be the product of the vegetable process, for either none, or scarce any, is found in the soils, or in rain water." In like manner Lampadius thought he had proved that plants could generate silica. The theory that plants agreed in all essentials with animals was still accepted by many men of science; some interesting developments were made by Erasmus Darwin (1800).

Between 1770 and 1800 work was done on the effects of vegetation on air that was destined to revolutionise the ideas of the function of plants in the economy of Nature, but its agricultural significance was not recognised until later. Priestley (1775), knowing that the atmosphere becomes vitiated by animal respiration, combustion, putrefaction, etc.,

and realising that some natural purification must go on, or life would not longer be possible, was led to try the effect of sprigs of living mint on vitiated air. He found that the mint made the air purer, and concludes "that plants, instead of affecting the air in the same manner with animal respiration, reverse the effects of breathing, and tend to keep the atmosphere pure and wholesome, when it is become noxious in consequence of animals either living, or breathing, or dying, and putrefying in it." But he had not yet discovered oxygen, and so could not give precision to his discovery: and when, later on, he did discover oxygen and learn how to estimate it, he unfortunately failed to confirm his earlier results because he overlooked a vital factor, the necessity of light. He was therefore unable to answer Scheele, who had insisted that plants, like animals, vitiate the air. It was Ingen-Housz (1779) who reconciled both views and showed that purification goes on in light only, whilst vitiation takes place in the darkness. Jean Senebier at Geneva had also arrived at the same result. He also studied the converse problem—the effect of air on the plant, and in 1782 argued that the increased weight of the tree in Van Helmont's experiment (p. 2) came from the fixed air. "Si donc l'air fixe, dissous dans l'eau de l'atmosphère, se combine dans la parenchyme avec la lumière et tous les autres élémens de la plante; si le phlogistique de cet air fixe est sûrement précipité dans les organes de la plante, si ce précipité reste, comme on le voit, puisque cet air fixe sort des plantes sous la forme d'air déphlogistiqué, il est clair que l'air fixe, combiné dans la plante avec la lumière, y laisse une matière qui n'y seroit pas, et mes expériences sur l'étiolement suffisent pour le démontrer." Later on Senebier translated his work into the modern terms of Lavoisier's system.

2. *The Modern Period*, 1800-1860.

(*a*) *The Foundation of Plant Physiology.*—We have seen that Home in 1757 pushed his inquiries as far as the methods

in vogue would permit, and in consequence no marked advance was made for forty years. A new method was wanted before further progress could be made, or before the new idea introduced by Senebier could be developed. Fortunately, this was soon forthcoming. To Théodore de Saussure, in 1804, son of the well-known de Saussure of Geneva, is due the quantitative experimental method which more than anything else has made modern agricultural chemistry possible: which formed the basis of subsequent work by Boussingault, Liebig, Lawes and Gilbert, and, indeed, still remains our safest method of investigation. Senebier tells us that the elder de Saussure was well acquainted with his work, and it is therefore not surprising that the son attacked two problems that Senebier had also studied—the effect of air on plants and the nature and origin of salts in plants. De Saussure grew plants in air or in known mixtures of air and carbon dioxide, and measured the gas changes by eudiometric analysis and the changes in the plant by "carbonisation." He was thus able to demonstrate the central fact of plant respiration—the absorption of oxygen and the evolution of carbon dioxide, and further to show the decomposition of carbon dioxide and evolution of oxygen in light. Carbon dioxide in small quantities was a vital necessity for plants, and they perished if it was artificially removed from the air. It furnished them not only with carbon, but also with some oxygen. Water is also decomposed and fixed by plants. On comparing the amount of dry matter gained from these sources with the amount of material that can enter through the roots even under the most favourable conditions, he concludes that the soil furnished only a very small part of the plant food. Small as it is, however, this part is indispensable: it supplies nitrogen—*une partie essentielle des végétaux*—which, as he had shown, was not assimilated direct from the air; and also ash constituents, *qui peuvent contribuer à former, comme dans les animaux, leur parties solides ou osseuses.* Further, he shows that the root is not a mere filter allowing any and every liquid to enter the plant; it has a special action and

takes in water more readily than dissolved matter, thus effecting a concentration of the solution surrounding it; different salts, also, are absorbed to a different extent. Passing next to the composition of the plant ash, he shows that it is not constant, but varies with the nature of the soil and the age of the plant; it consists mainly, however, of alkalis and phosphates. All the constituents of the ash occur in humus. If a plant is grown from seed in water there is no gain in ash: the amount found at the end of the plant's growth is the same as was present in the seed excepting for a relatively small amount falling on the plant as dust. Thus he disposes finally of the idea that the plant *generated* potash.

After the somewhat lengthy and often wearisome works of the earlier writers it is very refreshing to turn to de Saussure's concise and logical arguments and the ample verification he gives at every stage. But for years his teachings were not accepted, nor were his methods followed.

The two great books on agricultural chemistry then current still belonged to the old period. Thaer and Davy, while much in advance of Wallerius, the textbook writer of 1761, nevertheless did not realise the fundamental change introduced by de Saussure; it has always been the fate of agricultural science to lag behind pure science. Thaer published his *Grundsätze der rationellen Landwirtschaft* in 1809-1812: it had a great success on the Continent as a good, practical handbook, and was translated into English as late as 1844 by Cuthbert Johnson. In it he adopted the prevailing view that plants draw their carbon and other nutrients from the soil humus. "Die Fruchtbarkeit des Bodens," he says, "hängt eigentlich ganz vom Humus ab. Denn ausser Wasser ist er es allein, der den Pflanzen Nahrung gibt. So wie der Humus eine Erzeugung des Lebens ist, so ist er auch eine Bedingung des Lebens. Er gibt den Organismen die Nahrung. Ohne ihn lässt sich kein individuelles Leben denken." Davy's book (1813) grew out of the lectures which he gave annually at the Royal Institution on agricultural chemistry between 1802 and 1812;

it forms the last textbook of the older period. Whilst no great advance was made by Davy himself he carefully sifted the facts and hypotheses of previous writers, and gives us an account, which, however defective in places, represents the best accepted knowledge of the time, set out in the new chemical language. His great name gave the subject an importance it would not otherwise have had.[1] He did not accept de Saussure's conclusion that plants obtain their carbon chiefly from the carbonic acid of the air: some plants, he says, appear to be supplied with carbon chiefly from this source, but in general he supposes the carbon to be taken in through the roots. Oils are good manures because of the carbon and hydrogen they contain; soot is valuable, because its carbon is "in a state in which it is capable of being rendered soluble by the action of oxygen and water." Lime is useful because it dissolves hard vegetable matter. Once the organic matter has dissolved there is no advantage in letting it decompose further: putrid urine is less useful as manure than fresh urine, whilst it is quite wrong to cause farmyard manure to ferment before it is applied to the land. All these ideas have long been given up, and indeed there never was any sound experimental evidence to support them. It is even arguable that they would not have persisted so long as they did had it not been for Davy's high reputation. His insistence on the importance of the physical properties of soils—their relationship to heat and to water—was more fortunate and marks the beginning of soil physics, afterwards developed considerably by Schübler (1838). On the Continent, to an even greater extent than in England, it was held that plants drew their carbon and other nutrients from the soil humus, a view supported by the very high authority of Berzelius.[2]

[1] Thus Charles Lamb, *Essays of Elia* (1820-1823) in the "Old and New Schoolmaster," writes: "The modern schoolmaster is required to know a little of everything because his pupil is required not to be entirely ignorant of anything. He is to know something of pneumatics, of chemistry, the quality of soils, etc. . . ."

[2] J. J. Berzelius, *Lehrbuch d. Chemie*, übersetz. F. Wöhler, 3 Aufl., 1839, Bd. 8.

(*b*) *The Foundation of Agricultural Science.*—Hitherto experiments had been conducted either in the laboratory or in small pots: about 1834, however, Boussingault, who was already known as an adventurous traveller in South America, began a series of field experiments on his farm at Bechelbronn in Alsace. These were the first of their kind: to Boussingault, therefore, belongs the honour of having introduced the method by which the new agricultural science was to be developed. He reintroduced the quantitative methods of de Saussure, weighed and analysed the manures used and the crops obtained, and at the end of the rotation drew up a balance sheet, showing how far the manures had satisfied the needs of the crop and how far other sources of supply—air, rain, and soil—had been drawn upon. The results of one experiment are given in Table I on this page. At the end of the period the soil had returned to its original state of productiveness,

TABLE I.—STATISTICS OF A ROTATION. BOUSSINGAULT (1841).

	Weight in kilograms per hectare of					
	Dry Matter.	Carbon.	Hydrogen.	Oxygen.	Nitrogen.	Mineral Matter.
1. Beets	3172	1357·7	184·0	1376·7	53·9	199·8
2. Wheat	3006	1431·6	164·4	1214·9	31·3	163·8
3. Clover hay	4029	1909·7	201·5	1523·0	84·6	310·2
4. Wheat	4208	2004·2	230·0	1700·7	43·8	229·3
Turnips (catch crop)	716	307·2	39·3	302·9	12·2	54·4
5. Oats	2347	1182·3	137·3	890·9	28·4	108·0
Total during rotation	17478	8192·7	956·5	7009·0	254·2	1065·5
Added in manure	10161	3637·6	426·8	2621·5	203·2	3271·9
Difference not accounted for taken from air, rain, or soil	+7317	+4555·1	+ 529·7	+4387·5	+ 51·0	−2206·4

1000 kilograms per hectare = 16 cwt. per acre.

hence the dry matter, carbon, hydrogen, and oxygen not accounted for by the manure must have been supplied by the air and rain, and not by the soil. On the other hand, the manure afforded more mineral matter than the crop took off, the balance remaining in the soil. Other things being equal, he argued that the best rotation is one which yields the greatest amount of organic matter over and above what is present in the manure. No fewer than five rotations were studied, but it will suffice to set out only the nitrogen statistics (Table 2 on this page), which show a marked gain of nitrogen when the newer rotations are adopted, but not where wheat only is grown.

Now the rotation has not impoverished the soil, hence he concludes that " l'azote peut entrer directement dans l'organisme des plantes, si leur parties vertes sont aptes à le fixer."

TABLE 2.—NITROGEN STATISTICS OF VARIOUS ROTATIONS. BOUSSINGAULT (1841).

Rotation.	Kilograms per hectare.			
	Nitrogen in Manure.	Nitrogen in Crop.	Excess in Crop over that supplied in Manure.	
			Per Rotation.	Per Annum.
(1) Potatoes, (2) wheat, (3) clover, (4) wheat, turnips,[1] (5) oats	203·2	250·7	47·5	9·5
(1) Beets, (2) wheat, (3) clover, (4) wheat, turnips,[1] (5) oats	203·2	254·2	51·0	10·2
(1) Potatoes, (2) wheat, (3) clover, (4) wheat, turnips,[1] (5) peas, (6) rye	243·8	353·6	109·8	18·3
Jerusalem artichokes, two years	188·2	274·2	86·0	43·0[2]
(1) Dunged fallow, (2) wheat, (3) wheat	82·8	87·4	4·6	1·5
Lucerne, five years	224·0	1078·0	854	170·8

[1] Catch crop, *i.e.* taken in autumn after the wheat.

[2] This crop does not belong to the leguminosæ, but it is possible that the nitrogen came from the soil, and that impoverishment was going on.

Boussingault's work covers the whole range of agriculture and deals with the composition of crops at different stages of their growth, with soils, and with problems in animal nutrition. Unfortunately the classic farm of Bechelbronn did not remain a centre of agricultural research and the experiments came to an end after the war of 1870. Some of the work was summarised by Dumas and Boussingault (1841) in a very striking essay that has been curiously overlooked by agricultural chemists.

During this period (1830-1840) Carl Sprengel (1832) was studying the ash constituents of plants, which he considered were probably essential to nutrition. Schübler (1838) was working at soil physics, and a good deal of other work was quietly being done. No particularly important discoveries were being made, no controversies were going on, and no great amount of interest was taken in the subject.

But all this was changed in 1840 when Liebig's famous report to the British Association [1] upon the state of organic chemistry, published as *Chemistry in its Application to Agriculture and Physiology* (1840), came like a thunderbolt upon the world of science. With polished invective and a fine sarcasm he holds up to scorn the plant physiologists of his day for their continued adhesion, in spite of accumulated evidence, to the view that plants derive their carbon from the soil and not from the carbonic acid of the air. "All explanations of chemists must remain without fruit, and useless, because, even to the great leaders in physiology, carbonic acid, ammonia, acids, and bases are sounds without meaning, words without sense, terms of an unknown language, which awake no thoughts and no associations." The experiments quoted by the physiologists in support of their view are all "valueless for the decision of any question." "These experiments are considered by them as convincing proofs, whilst they are fitted only to awake pity." Liebig's ridicule did what neither de Saussure's

[1] There is no record of this Report ever having been presented to the Association.

nor Boussingault's logic had done: it finally killed the humus theory. Only the boldest would have ventured after this to assert that plants derive their carbon from any source other than carbon dioxide, although it must be admitted that we have no proof that plants really do obtain all their carbon in this way. Thirty years later, in fact, Grandeau (1872) adduced evidence that humus may, after all, contribute something to the carbon supply, and his view found some acceptance in France;[1] for this also, however, convincing proof is lacking. But for the time carbon dioxide was considered to be the sole source of the carbon of plants. Hydrogen and oxygen came from water, and nitrogen from ammonia. Certain mineral substances were essential: alkalis were needed for neutralisation of the acids made by plants in the course of their vital processes, phosphates were necessary for seed formation, and potassium silicates for the development of grasses and cereals. The evidence lay in the composition of the ash: plants might absorb anything soluble from the soil, but they excreted from their roots whatever was non-essential. The fact of a substance being present was therefore sufficient proof of its necessity.

Plants, Liebig argued, have an inexhaustible supply of carbonic acid in the air. But time is saved in the early stages of plant growth if carbonic acid is being generated in the soil, for it enters the plant roots and affords extra nutrient over and above what the small leaves are taking in. Hence a supply of humus, which continuously yields carbonic acid, is advantageous. Further, the carbonic acid attacks and dissolves some of the alkali compounds of the soil and thus increases the mineral food supply. The true function of humus is to evolve carbonic acid.

The alkali compounds of the soil are not all equally soluble. A weathering process has to go on, which is facilitated by liming and cultivation, whereby the comparatively insoluble

[1] See *e.g.* L. Cailletet (*C.R.*, 1911, **152**, 1215), Jules Lefèvre (*ibid.*, 1905, **141**, 211-213), and J. Laurent (*Rev. gén. bot.*, 1904, **16**, 14).

compounds are broken down to a more soluble state. The final solution is effected by acetic acid excreted by the plant roots, and the dissolved material now enters the plant.

The nitrogen is taken up as ammonia, which may come from the soil, from added manure, or from the air. In order that a soil may remain fertile it is necessary and sufficient to return in the form of manure the mineral constituents and the nitrogen that have been taken away. When sufficient crop analyses have been made it will be possible to draw up tables showing the farmer precisely what he must add in any particular case.

An artificial manure known as Liebig's patent manure was made up on these lines and placed on the market.

Liebig's book was meant to attract attention to the subject, and it did ; it rapidly went through several editions, and as time went on Liebig developed his thesis, and gave it a quantitative form : " The crops on a field diminish or increase in exact proportion to the diminution or increase of the mineral substances conveyed to it in manure." He further adds what afterwards became known as the Law of the Minimum, " by the deficiency or absence of *one* necessary constituent, all the others being present, the soil is rendered barren for all those crops to the life of which *that one* constituent is indispensable." These and other amplifications in the third edition, 1843, gave rise to much controversy. So much did Liebig insist, and quite rightly, on the necessity for alkalis and phosphates, and so impressed was he by the gain of nitrogen in meadow land supplied with alkalis and phosphates alone, and by the continued fertility of some of the fields of Virginia and Hungary and the meadows of Holland, that he began more and more to regard the atmosphere as the source of nitrogen for plants. Some of the passages of the first and second editions urging the necessity of ammoniacal manures were deleted from the third and later editions. " If the soil be suitable, if it contain a sufficient quantity of alkalis, phosphates, and sulphates, nothing will be wanting. The plants

will derive their ammonia from the atmosphere as they do carbonic acid," he writes in the *Farmer's Magazine*.[1] Ash analysis led him to consider the turnip as one of the plants "which contain the least amount of phosphates and therefore require the smallest quantity for their development." These and other practical deductions were seized upon and shown to be erroneous by Lawes and Gilbert (1847) who had for some years been conducting vegetation experiments. Lawes does not discuss the theory as such, but tests the deductions Liebig himself draws and finds them wrong. Further trouble was in store for Liebig; his patent manure when tried in practice *had failed*. This was unfortunate, and the impression in England at any rate was, in Philip Pusey's words: "The mineral theory, too hastily adopted by Liebig, namely, that crops rise and fall in direct proportion to the quantity of mineral substances present in the soil, or to the addition or abstraction of these substances which are added in the manure, has received its death-blow from the experiments of Mr. Lawes."

And yet the failure of the patent manure was not entirely the fault of the theory, but only affords further proof of the numerous pitfalls of the subject. The manure was sound in that it contained potassium compounds and phosphates (it ought, of course, to have contained nitrogen compounds), but it was unfortunately rendered insoluble by fusion with lime and calcium phosphate so that it should not too readily wash out in the drainage water. Not till Way had shown in 1850 that *soil precipitates soluble salts of ammonium, potassium, and phosphates* was the futility of the fusion process discovered, and Liebig (1851) saw the error he had made.

Meanwhile the great field experiments at Rothamsted had been started by Lawes and Gilbert in 1843. These experiments were conducted on the same general lines as those begun earlier

[1] *Farmer's Magazine*, 1847, **16**, 511. A good summary of Liebig's position is given in his *Letters on Chemistry*, 34th letter, 3rd edition, p. 519, 1851.

by Boussingault, but they have the advantage that they are still going on, having been continued year after year on the same ground without alteration, except in occasional details, since 1852. The mass of data now accumulated is considerable and it is being treated by modern statistical methods. Certain conclusions are so obvious, however, that they can be drawn on mere inspection of the data. By 1855 the following points were definitely settled :— [1]

1. Crops require phosphates and salts of the alkalis, but the composition of the ash does not afford reliable information as to the amounts of each constituent needed, *e.g.* turnips require large amounts of phosphates, although only little is present in their ash. Some of the results are :—

Composition of ash, per cent. (1860 crop)—		Yield of turnips, tons per acre (1843)—	
K_2O	44·8	Unmanured . . .	4·5
P_2O_5	7·9	Superphosphate . .	12·8
		,, + potassic salts	11·9

2. Non-leguminous crops require a supply of some nitrogenous compounds, nitrates and ammonium salts being almost equally good. Without an adequate supply no increases of growth are obtained, even when ash constituents are added. The amount of ammonia obtainable from the atmosphere is insufficient for the needs of crops. Leguminous crops behave abnormally.

3. Soil fertility may be maintained for some years at least by means of artificial manures.

4. The beneficial effect of fallowing lies in the increase brought about in the available nitrogen compounds in the soil.

Although many of Liebig's statements were shown to be wrong, the main outline of his theory as first enunciated stands. It is no detraction that de Saussure had earlier

[1] Lawes and Gilbert's papers are collected in ten volumes of *Rothamsted Memoirs*, and the general results of their experiments are summarised by Hall in *The Book of the Rothamsted Experiments*. A detailed investigation of the early experiments of Lawes in their relation to the discovery of superphosphate has been made by Max Speter in *Superphosphate*, 1935, 8.

published a somewhat similar, but less definite view of nutrition: Liebig had brought matters to a head and made men look at their cherished, but unexamined, convictions. The effect of the stimulus he gave can hardly be over-estimated, and before he had finished, the essential facts of plant nutrition were settled and the lines were laid down along which scientific manuring was to be developed. The water cultures of Knop and other plant physiologists showed conclusively that potassium, magnesium, calcium, iron, phosphorus, along with sulphur, carbon, nitrogen, hydrogen, and oxygen are all necessary for plant life. The list differs from Liebig's only in the addition of iron and the withdrawal of silica; but even silica, although not strictly essential, is advantageous for the nutrition of cereals.

In two directions, however, the controversies went on for many years. Farmers were slow to believe that "chemical manures" could ever do more than stimulate the crop, and declared they must ultimately exhaust the ground. The Rothamsted plots falsified this prediction; manured year after year with the same substances and sown always with the same crops, they even now, after ninety years of chemical manuring, continue to produce good crops, although secondary effects have sometimes set in. In France the great missionary was Georges Ville (1879), whose lectures were given at the experimental farm at Vincennes during 1867 and 1874-1875. He went even further than Lawes and Gilbert, and maintained that artificial manures were not only more remunerative than dung, but were the only way of keeping up fertility. In recommending mixtures of salts for manure he was not guided by ash analysis but by field trials. For each crop one of the four constituents, nitrogen compounds, phosphates, lime, and potassium compounds (he did not consider it necessary to add any others to his manures) was found by trial to be more wanted than the others and was therefore called the "dominant" constituent. Thus for wheat he obtained the following results, and therefore concluded that on his soil wheat required

a good supply of nitrogen, less phosphate, and still less potassium :—

	Crop per acre. Bushels.
Normal manure	43
Manure without lime	41
,, ,, potash	31
,, ,, phosphate	26½
,, ,, nitrogen	14
Soil without manure	12

Other experiments of the same kind showed that nitrogen was the dominant for all cereals and beetroot, potassium for potatoes and vines, phosphates for the sugar cane. An excess of the dominant constituent was always added to the crop manure. The composition of the soil had to be taken into account, but soil analysis was no good for the purpose. Instead he drew up a simple scheme of plot trials to enable farmers to determine for themselves just what nutrient was lacking in their soil. His method was thus essentially empirical, but it still remains the best we have : his view that chemical manures are always better and cheaper than dung is, however, too narrow and has not survived.

The second controversy dealt with the source of nitrogen in plants. Priestley had stated that a plant of *Epilobium hirsutum* placed in a small vessel absorbed during the course of the month seven-eighths of the air present. De Saussure, however, denied that plants assimilated gaseous nitrogen. Boussingault's pot experiments (1838) showed that peas and clover could get nitrogen from the air while wheat could not, and his rotation experiments emphasised this distinction. He himself did not make as much of this discovery as he might have done, but Dumas and Boussingault (1841) fully realised its importance.

Liebig, as we have seen, maintained that ammonia, but not gaseous nitrogen, was taken up by plants, a view confirmed by Lawes, Gilbert, and Pugh (1861) in the most rigid demonstration that had yet been attempted. Plants of several natural orders, including the leguminosæ, were grown

in surroundings free from ammonia or any other nitrogen compound. The soil was burnt to remove all trace of nitrogen compounds while the plants were kept throughout the experiment under glass shades, but supplied with washed and purified air and with pure water. In spite of the ample supply of mineral food the plants languished and died: the conclusion seemed irresistible that plants could not utilise gaseous nitrogen. For all non-leguminous crops this conclusion agreed with the results of field trials. But there remained the very troublesome fact that leguminous crops required no nitrogenous manure and yet they contained large quantities of nitrogen, and also enriched the soil considerably in this element. Where had the nitrogen come from? The amount of combined nitrogen brought down by the rain was found to be far too small to account for the result. For years experiments were carried on, but the problem remained unsolved. Looking back over the papers [1] one can see how very close some of the older investigators were to the discovery of the cause of the mystery: in particular Lachmann (1858) carefully examined the structure of the nodules, which he associated with the nutrition of the plant, and showed that they contained "vibrionenartige" organisms. His paper, however, was published in an obscure journal and attracted little attention. W. O. Atwater in 1881 and 1882 showed that peas acquired large quantities of nitrogen from the air, and later suggested that they might "favour the action of nitrogen-fixing organisms." [2] But he was too busily engaged to follow the matter up, and once again an investigation in agricultural chemistry had been brought to a standstill for want of new methods of attack.

[1] A summary of the voluminous literature is contained in Löhnis' *Handbuch der Landw. Bakteriologie*, pp. 646 *et seq.*

[2] *Amer. Chem. J.*, 1885, **6**, 365, and **8**, 327.

The Beginnings of Soil Bacteriology.

It had been a maxim with the older agricultural chemists that "corruption is the mother of vegetation." Animal and vegetable matter had long been known to decompose with formation of nitrates: indeed nitre beds made up from such decaying matter were the recognised source of nitrates for the manufacture of gunpowder during the European wars of the seventeenth and eighteenth centuries.[1] No satisfactory explanation of the process had been offered, although the discussion of rival hypotheses continued up till 1860, but the conditions under which it worked were known and on the whole fairly accurately described.

No connection was at first observed between nitrate formation and soil productiveness. Liebig (1855) rather diverted attention from the possibility of tracing what now seems an obvious relationship by regarding ammonia as the essential nitrogenous plant nutrient, though he admitted the possible suitability of nitrates. Way came much nearer to the truth. In 1856 he showed that nitrates were formed in soils to which nitrogenous fertilisers were added. Unfortunately he failed to realise the significance of this discovery. He was still obsessed with the idea that ammonia was essential to the plant, and he believed that ammonia, unlike other nitrogen compounds, could not change to nitrate in the soil, but was absorbed by the soil by the change he had already described (p. 18). But he only narrowly missed making an important advance in the subject, for after pointing out that nitrates are comparable with ammonium salts as fertilisers he writes: "Indeed the French chemists are going further, several of them now advocating the view that it is in the form of nitric acid that plants make use of compounds of nitrogen. With this view I do not myself at present coincide: and it is sufficient here to admit that nitric acid in the form of nitrates has at least a very high value as a manure."

[1] "Instructions sur l'établissement des nitrières, publié par les Régisseurs généraux des Poudres et Salpètre." Paris, 1777.

It was not till ten years later, and as a result of work by plant physiologists, that the French view prevailed over Liebig's, and agricultural investigators recognised the importance of nitrates to the plant and of nitrification to soil fertility. It then became necessary to discover the cause of nitrification.

During the 'sixties and 'seventies great advances were being made in bacteriology, and it was definitely established that bacteria bring about putrefaction, decomposition, and other changes; it was therefore conceivable that they were the active agents in the soil, and that the process of decomposition there taking place was not the purely chemical "eremacausis" Liebeg had postulated. Pasteur himself had expressed the opinion that nitrification was a bacterial process. The new knowledge was first brought to bear on agricultural problems by Schloesing and Müntz (1877) during a study of the purification of sewage water by land filters. A continuous stream of sewage was allowed to trickle down a column of sand and limestone so slowly that it took eight days to pass. For the first twenty days the ammonia in the sewage was not affected, then it began to be converted into nitrate; finally all the ammonia was converted during its passage through the column, and nitrates alone were found in the issuing liquid. Why, asked the authors, was there a delay of twenty days before nitrification began? If the process were simply chemical, oxidation should begin at once. They therefore examined the possibility of bacterial action and found that the process was entirely stopped by a little chloroform vapour, but could be started again after the chloroform was removed by adding a little turbid extract of dry soil. Nitrification was thus shown to be due to micro-organisms—"organised ferments," to use their own expression.

Warington (1878) had been investigating the nitrates in the Rothamsted soils, and at once applied the new discovery to soil processes. He showed that nitrification in the soil is stopped by chloroform and carbon disulphide; further, that

solutions of ammonium salts could be nitrified by adding a trace of soil. By a careful series of experiments described in his four papers to the Chemical Society he found that there were two stages in the process and two distinct organisms: the ammonia was first converted into nitrite and then to nitrate. But he failed altogether to obtain the organisms, in spite of some years of study, by the gelatin plate methods then in vogue. The reason was discovered later: the organisms will not grow in presence of nitrogenous organic matter. Not till 1890 did Winogradsky (1890) succeed in isolating them, and thus completing the evidence.

Warington established definitely the fact that nitrogen compounds rapidly change to nitrates in the soil, so that whatever compound is supplied as manure, plants get practically nothing but nitrate as food. This closed the long discussion as to the nitrogenous food of non-leguminous plants; in natural conditions they take up nitrates only (or at any rate chiefly), because the activities of the nitrifying organisms leave them no option. The view that plants assimilate gaseous nitrogen has from time to time been revived,[1] but it is not generally accepted.

The apparently hopeless problem of the nitrogen nutrition of leguminous plants was soon to be solved. In a striking series of sand cultures Hellriegel and Wilfarth (1888) showed that the growth of non-leguminous plants, barley, oats, etc., was directly proportional to the amount of nitrate supplied, the duplicate pots agreeing satisfactorily; while in the case of leguminous plants no sort of relationship existed and duplicate pots failed to agree. After the seedling stage was passed the leguminous plants grown without nitrate made no further progress for a time, then some of them started to grow and did well, while others failed. This stagnant period was not

[1] *E.g.* Th. Pfeiffer and E. Franke, *Landw. Vers.-Sta.*, 1896, **46**, 117; Thos. Jamieson, *Aberdeen Res. Assoc. Repts.*, 1905-1908; C. B. Lipman and J. K. Taylor, *J. Franklin Inst. Calif.*, 1924, p. 475.

seen where nitrate was supplied. Two of their experiments are given in Table 3.

TABLE 3.—RELATION BETWEEN NITROGEN SUPPLY AND PLANT GROWTH. HELLRIEGEL AND WILFARTH (1888).

Nitrogen in the calcium nitrate supplied per pot, grams	none	·056	·112	·168	·224	·336
Weight of oats obtained (grain and straw)	·3605 ·4191	5·9024 5·8510 5·2867	10·9814 10·9413	15·9974	21·2732 21·4409	30·1750
Weight of peas obtained (grain and straw)	·551 3·496 5·233	·9776 1·3037 4·1283	4·9146 9·7671 8·4969	5·6185	9·7252 6·6458	11·3520

Analysis showed that the nitrogen contained in the oat crop and sand at the end of the experiment was always a little less than that originally supplied, but was distinctly greater in the case of peas; the gain in three cases amounted to 0·910, 1·242, and 0·789 grm. per pot respectively. They drew two conclusions: (1) the peas took their nitrogen from the air; (2) the process of nitrogen assimilation was conditioned by some factor that did not come into their experiment except by chance. In trying to frame an explanation they connected two facts that were already known. Berthelot (1885) had made experiments to show that certain micro-organisms in the soil can assimilate gaseous nitrogen. It was known to botanists that the nodules on the roots of leguminosæ contained bacteria.[1] Hellriegel and Wilfarth, therefore, supposed that the bacteria in the nodules assimilated gaseous nitrogen, and then handed on some of the resulting nitrogenous compounds to the plant. This hypothesis was shown to be well founded by the following facts:—

1. In absence of nitrates peas made only small growth

[1] This had been demonstrated by Lachmann (1858) (p. 21) and by Woronin (1866). Eriksson in 1874 (Doctor's dissertation, abs. in *Botan. Ztg.*, 1874, **32**, 381-384) carried on the investigation, while G. Brunchorst in 1885, *Ber. Deut. Bot. Ges.*, **3**, 241, gave the name "bacteroids."

and developed no nodules in sterilised sand; when calcium nitrate was added they behaved like oats and barley, giving regular increases in crop for each increment of nitrates (the discordant results of Table 3 were obtained on unsterilised sand).

2. They grew well and developed nodules in sterilised sand watered with an extract of arable soil.

3. They sometimes did well and sometimes failed when grown without soil extract and without nitrate in *unsterilised* sand, which might or might not contain the necessary organisms. An extract that worked well for peas might be without effect on lupins or serradella. In other words, the organism is specific.

Hellriegel and Wilfarth read their paper and exhibited some of their plants at the Naturforscher-Versammlung at Berlin in 1886. Gilbert was present at the meeting, and on returning to Rothamsted repeated and confirmed the experiments. At a later date Schloesing *fils* and Laurent (1892) showed that the weight of nitrogen absorbed from the air was approximately equal to the gain by the plant and the soil, and thus finally clinched the evidence.

	Control.	Peas.	Mustard.	Cress.	Spurge.
Nitrogen lost from the air, mgm.	1·0	134·6	− 2·6	− 3·8	− 2·4
Nitrogen gained by crop and soil, mgm. . . .	4·0	142·4	− 2·5	2·0	3·2

The organism was isolated by Beijerinck (p. 391) and called *Bacillus radicicola.*

Thus another great controversy came to an end, and the discrepancy between the field trials and the laboratory experiments of Lawes, Gilbert, and Pugh was cleared up. The laboratory experiments gave the correct conclusion that leguminous plants, like non-leguminous plants, have themselves no power of assimilating gaseous nitrogen; this power belongs

to the bacteria associated with them. But so carefully was all organic matter removed from the soil, the apparatus, and the air in endeavouring to exclude all trace of ammonia, that there was no chance of infection with the necessary bacteria. Hence no assimilation could go on. In the field trials the bacteria were active, and here there was a gain of nitrogen.

The general conclusion that bacteria are the real makers of plant food in the soil, and are, therefore, essential to the growth of all plants, was developed by Wollny (1884) and Berthelot (1888). It was supposed to be proved by Laurent's (1886) experiments.[1] He grew buckwheat on humus obtained from well-rotted dung, and found that plants grew well on the untreated humus, but only badly on the humus sterilised by heat. When, however, soil bacteria were added to the sterilised humus (by adding an aqueous extract of unsterilised soil) good growth took place. The experiment looks convincing, but is really unsound. When a rich soil is heated some substance is formed toxic to plants. The failure of the plants on the sterilised humus was, therefore, not due to absence of bacteria, but to the presence of a toxin. No one has yet succeeded in carrying out this fundamental experiment of growing plants in two soils differing only in that one contains bacteria while the other does not.

Similarly Caron [2] thought he had direct evidence of the beneficial effect of bacteria in plant growth, but in reality the evidence is unsatisfactory.

The close connection between bacterial activity and the nutrition of plants is, however, fully justified by many experiments, and forms a considerable part of our modern conception of the soil as a producer of crops, as will appear in the following chapters.

[1] See also E. Duclaux, *C.R.*, 1885, **100**, 66.
[2] *Landw. Vers.-Sta.*, 1895, **45**, 401.

The Rise of Modern Knowledge of the Soil: the Search for Fresh Factors and the Return to Field Studies.

Further investigation of soil problems has shown that they are more complex than was at first supposed. Soils can no longer satisfactorily be divided into a few simple groups: sands, clays, loams, etc., according to their particle size; nor can attention be confined to the surface layer. It is necessary to take account of their history. The properties of a soil depend not only on its parent material but also on the climatic, vegetation and other factors to which it has been subjected.

The Russian investigators Dokuchazev (1883), Glinka (1914), Polynov (1936) and others introduced the modern methods of soil classification which have since been considerably developed.

The relations of the plant to the soil are also recognised as highly complex. The older workers had thought of soil fertility as a simple chemical problem; the early bacteriologists thought of it as bacteriological. Wollny (1878-1898) and F. H. King (1899) showed that the physical properties of the soil already studied by Davy and Schübler play a fundamental part in soil fertility. Van Bemmelen showed that soil has colloidal properties and present-day workers have observed in the soil many of the phenomena investigated in laboratories devoted to the study of colloids. Whitney and Cameron at Washington greatly widened the subject by revealing the importance of the soil solution and introducing the methods and principles of physical chemistry. Russell and Hutchinson at Rothamsted showed that bacterial action alone would not account for the biological phenomena in the soil, but that other organisms are also concerned, and subsequent work in the Rothamsted laboratories and elsewhere has revealed the presence of a complex soil population, the various members of which react on one another and on the growing plant.

Fresh advances are continually being made in the vigorous experiment stations in the United States, the British Empire,

Europe, and Japan. In the main the work is analytical and involves a search for new factors: synthesis is hardly attempted as yet. As the factors are discovered attempts are made to give them mathematical expression. Thus Liebig's Law of the Minimum and F. F. Blackman's Limiting Factors are expressed mathematically by Mitscherlich (p. 136), V. H. Blackman [1] expresses plant growth by the "compound interest law," Maskell and the Rothamsted workers give a more complex expression, while the modern agricultural chemist is acquiring a taste for mathematical formulæ and constants unknown to the older generation of workers.

In modern experimental stations the tendency is towards team work. As an instance chosen because it is best known to the writer: at the Rothamsted Experimental Station, instead of a number of isolated individuals, there is a body of workers investigating the subject, each from his own special point of view, but each fully cognisant of the work of the others, and periodically submitting his results to discussion by them. Separate workers investigate respectively the bacteria, protozoa, fungi, algæ, helminths, and insects of the soil; in addition physical and organic chemists are studying the soil conditions, while others are concerned in the study of the growing plant. A body of workers by harmonious co-operation is able to make advances that would be impossible for any single individual, however brilliant.

The nature of the subject necessitates a further departure from the usual procedure. In purely laboratory investigations it is customary to adopt the Baconian method in which factors are studied one at a time, all others being kept constant except the particular one under investigation. In dealing with soils in natural conditions, however, it is impossible to proceed in this way: climatic factors will not be kept constant, and however careful the effort to ensure equality of conditions there is always the probability, and sometimes the certainty,

[1] *Ann. Bot.*, 1919, **33**, 353.

that the variable factor under investigation is interacting with climatic factors and exerting indirect effects which modify or even obscure the direct effects it is desired to study.

Of recent years statisticians have devised methods for dealing with cases where several factors are varying simultaneously. The data obtained by the various workers at Rothamsted are therefore examined by a statistician who endeavours to disentangle the effects of various factors and to state a number of probable relationships which can then be investigated in the laboratory by the ordinary single factor method.

The experimental procedure in soil investigations has greatly improved in the last few years. Laboratory and pot cultures methods have changed out of all recognition and, even more important, there is a growing tendency to study the soil *in situ* and in relation to its surroundings. The study of the soil has been regarded as an independent natural science and has been given a separate name, Pedology—which, however, has already been applied to another subject and in any case has not yet found its way into the standard English dictionaries.

This increased interest in the soil has shown itself in two directions. The development of soil surveys has encouraged an enormous development of soil studies *in situ;* and the introduction of modern statistical methods has given to field experiments a new value they completely lacked before. In the past field experiments were always weakened by the unknown errors due to the circumstances that the soil of one plot was never strictly comparable with the soil of another. Modern methods of field plot technique have overcome this difficulty and yield results to which a definite value can be assigned so that the data can be utilised in further investigations.

CHAPTER II.

SOIL CONDITIONS AFFECTING PLANT GROWTH.

THE following six soil factors profoundly affect the growth of plants :—

1. Water supply.
2. Air supply.
3. Temperature.
4. Supply of plant nutrients.
5. Various injurious factors.
6. Depth of soil.

The plant may be affected in four different ways : in the rate of growth, in the character or habit of growth, in its composition at different stages, and in the amount of plant substance finally obtained : or, using agricultural terms, the yield.

Of these factors, water and nutrient supplies, and the various injurious factors, have been most fully investigated by plant physiologists and agriculturists, and they have been most fully brought under control by soil experts : the methods are embodied in the art and science of soil management. The other factors are of equal importance, and if they have been less studied by soil experts it is mainly because air supply to the roots and soil temperatures are intimately bound up with the water content of the soil.

The root actions most closely associated with the soil are the absorption of water, the uptake of dissolved salts, and respiration. The first two are fundamentally distinct and have no causal connection ; they are, however, influenced by each

other. Thus the absorption of water, while an entirely different process from the uptake of nutrient salts, is considerably lessened in presence of salts. Respiration and uptake of salts are more closely associated, and an increased oxygen supply to the roots is usually associated with an increased uptake of salts.

Respiration is a continuous process, essential to the plant throughout its whole life; if it is stopped for any length of time the part of the root affected dies. Water absorption is also continuous, but it is more important at some periods than at others and at all times the plant can subsist for a while without fresh supplies. But the uptake of salts is not continuous; it occurs chiefly during the early part of the life of the plant, and is of much more significance then than later on.

Effect of Water Supply.[1]

The leaves of plants are continuously giving off water vapour into the air, and this evaporation or "transpiration" is made good by a continuous uptake of water by the roots. The process can be checked and ultimately stopped by saturating the air with water vapour; the plant then continues its growth without suffering, indeed in some cases with advantage, so that this procedure is sometimes adopted in glasshouse practice. Transpiration is also checked and finally stopped by withholding fresh supplies of water from the root; the cells then lose their turgidity, the plant wilts and ceases to grow; it dies if the water is long withheld.

During their growth most annual plants absorb from the soil in temperate climatic conditions some 300 to 500 units of water for each unit dry matter formed. The transpiration of water is particularly great during the rapidly growing period and it falls off considerably during maturation.

[1] For a full discussion see N. A. Maximov, *The Plant in Relation to Water*. Allen & Unwin, London, 1929.

The Effect of Varying Water Supply on Plant Growth: Controlled Water Supply.

The relationship between the final amount of growth and the supply of water is shown by Hellriegel's experiments (1883, Table 4) with barley grown under favourable conditions in sand cultures.

Table 4.—Growth of Barley with Varying Supply of Water. Hellriegel (1883).

Amount of water	5	10	20	30	40	60	80
Dry matter in grain, grms.	nil	0·72	7·75	9·73	10·51	9·96	8·77
Dry matter in straw, grms.	·12	1·80	5·50	8·20	9·64	11·00	9·47
1 grain weighed, mgms.	—	23	35	36	34	32	32

100 represents the amount of water required to saturate the sand.

The yield both of grain and of straw increases as the water increases up to a point; then, however, it falls off. The increase in straw continues longer than that of grain (Fig. 1). A. T. Legg repeated the experiment with the same result, and satisfactorily explained the fall in yield of grain. The numbers of shoots, ears, and flowers increased with increasing water supply, but the proportion of sterile flowers increased also, hence the grain decreased. The size and coarseness of the individual grains, however, increased with the water supply.

Table 5.—Yield of Wheat with Increasing Quantities of Irrigation Water, Greenville Farm, Utah. Widtsoe.[1]

Irrigation water: inches	5·0	7·5	15·0	25·30	40-60
Yield of wheat, lb. per acre	4969	5545	6279	6672	7999
Grain, per cent. of total weight	44·4	43·2	40·8	38·6	32·9
Ratio grain/straw	0·80	0·76	0·69	0·63	0·49
Lb. of water supplied per lb. of dry matter obtained	856	869	1038	1317	1809

Rainfall, 13·74 inches.

[1] *Utah Agric. Expt. Sta., Bulls.* 115-120, 1912.

Similar results are obtained in the field. Widtsoe's measurements at the Greenville Experimental Farm, Utah (1912),

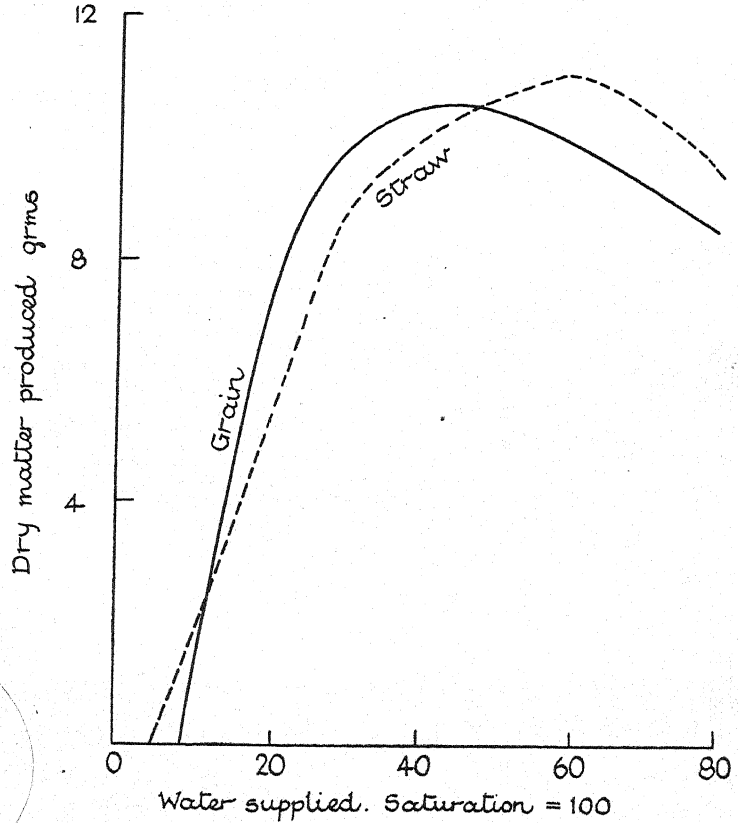


FIG. 1.—Relationship between yield of barley and supply of water (Hellriegel, 1883).

are given in Table 5 : the yield increases with increasing water supply, the straw more than the grain.

WATER SUPPLY UNCONTROLLED : NATURAL CONDITIONS ONLY.

The relationships between water supply and plant growth are at their simplest in semi-arid conditions where the amount of growth is largely determined by, and almost proportional

to, the rainfall. The method of investigation is to measure the amount of water in the soil at regular intervals during growth and to record the rainfall : then to make up a balance sheet showing the water supply at the beginning and at the end of plant growth ; the difference gives the amount transpired by the plant *plus* the amount lost by evaporation and drainage, if any, from the soil. J. S. Cole and O. R. Matthews (1923) found that during the growth of spring wheat in the

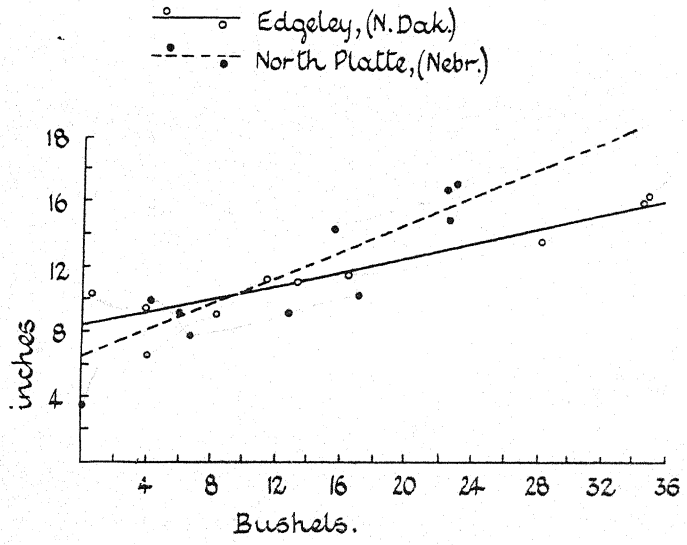


FIG. 2.—Water lost (measured as inches of rain) from soil during growth of spring wheat (Cole and Matthews, *U.S. Dept. of Agric. Bull.* 1004, 1923).

Great Plains of the Western United States a certain amount of water is evaporated whether there is any crop or not, but beyond this the additional water removed from the soil is proportional to the crop whatever the season : the data are reasonably well fitted by linear regression equations (Fig. 2). Exceptions occur when some catastrophe, such as a spell of hot winds, has severely damaged the crop. The basal water consumption varied at the different stations from 4 inches in

the north to 10 inches in the south ; the slope of the curve also varied ; these constants are apparently functions of climatic environment.

The curve brings out clearly the fact that the total loss of water is proportionately less for a large crop than for a small one : any device that increases the crop yield, such as improvements in variety, cultivation or manuring, enables a better use to be made of the water : the effect is the same as additional rainfall. And further, having determined the regression equation for a particular station it becomes possible to forecast the probable effect of additional rainfall on the yield.

In humid regions, where the water supply is often optimal or even superoptimal, the relationships between moisture supply and yield are frequently more complex, other factors often having a more dominant effect. The top part of Hellriegel's curves (Fig. 1) gives an approximate representation : additional supplies being sometimes advantageous, sometimes ineffective, sometimes harmful. No sufficient data have accumulated to permit of detailed study of the relationships between soil moisture and plant growth, but R. A. Fisher and his pupils at Rothamsted have studied the effect of rainfall on the yield of various crops, and shown that it depends on the time when the rain comes and on the supplies of plant nutrients in the soil.

The simplest case is afforded by the Broadbalk wheat field where a considerable part of the rainfall effect is linear, *i.e.* it increases or decreases proportionally as the rainfall is higher or lower than the average (Fig. 3). Usually, however, the effects are more complex, the linear effects being small in comparison with the others.[1]

[1] *E.g.* for barley and mangolds at Rothamsted (J. Wishart and Winifred A. Mackenzie, *J. Agric. Sci.*, 1930, **20**, 417, for barley ; R. J. Kalamkar, *ibid.*, 1933, **23**, 571, for mangolds), and for wheat and barley at Woburn (W. G. Cochran, in *Fifty Years of Field Experiments at the Woburn Experimental Station*, Rothamsted Monographs, 1936).

In addition to the direct action on the plant various changes take place in the soil as the result of the higher rainfall, and these in their turn affect the plant growth.

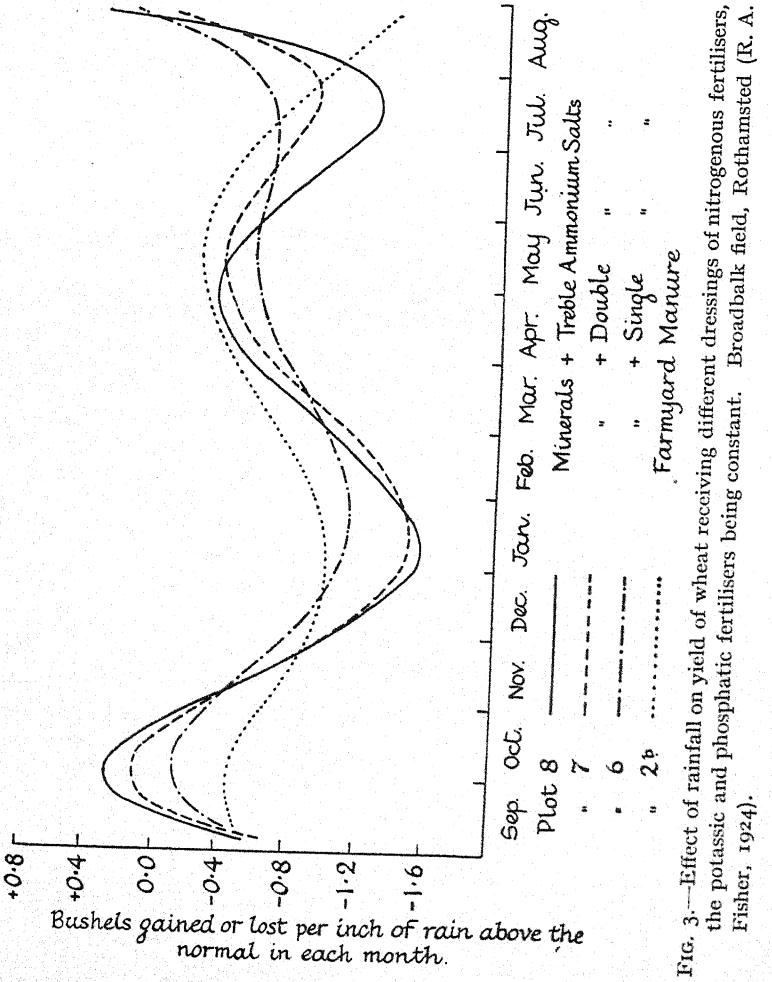


FIG. 3.—Effect of rainfall on yield of wheat receiving different dressings of nitrogenous fertilisers, the potassic and phosphatic fertilisers being constant. Broadbalk field, Rothamsted (R. A. Fisher, 1924).

RELATION BETWEEN WATER UPTAKE AND AMOUNT OF PLANT GROWTH; THE TRANSPIRATION RATIO.

So long as the amount of water supplied to the plant is below the optimum the total uptake of water corresponds fairly

well with the amount of plant growth and better than with uptake of nutrients (Fig. 4).[1]

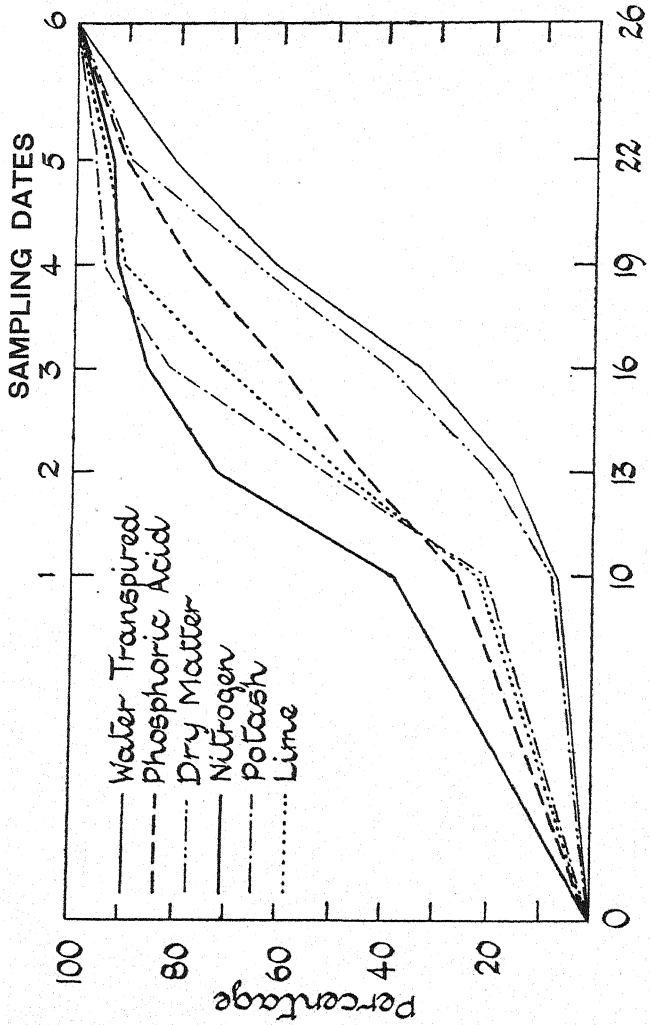


FIG. 4.—Transpiration of water, uptake of nutrients from soil, and production of dry matter in barley plants (A. E. V. Richardson and H. C. Trumble, *South Australia Journ. Dept. Agric.*, 1928, **32**, 224).

The amount of water transpired per unit of dry matter formed is called the transpiration coefficient or ratio. The

[1] See also A. E. V. Richardson, H. C. Trumble, and R. E. Shapter, *Aust. Counc. Sci. Indust. Res. Bull.* No. 49, 1931.

expression is convenient for the agriculturist in dry or irrigated districts, and has fully justified itself; but it is in no sense a constant. Its numerical value is profoundly affected by environmental conditions, but tends to be lower for some plants, and even for some varieties, than for others, and so it can be used by plant breeders seeking for varieties suitable for dry conditions.[1]

J. B. Lawes in 1850 indicated the range of variation between various crops, and showed that for some crops, at any rate, it was lowered by increasing the food supply. Of the later determinations those of Briggs and Shantz (Table 6) cover the

TABLE 6.—TRANSPIRATION COEFFICIENTS, *i.e.* WEIGHT OF WATER TRANSPIRED DURING THE PRODUCTION OF UNIT WEIGHT OF DRY MATTER. BRIGGS AND SHANTZ (1912).

Crop.	Extreme Values for Different Varieties.	Mean Value for Crop.
Proso	268 to 341	293
Millet	261 to 444	310
Sorghum	285 to 467	322
Maize	315 to 413	368
Wheat	473 to 559	513
Barley	502 to 556	534
Oats	559 to 622	597
Flax	—	905
Sugar beet	—	397
Potato	—	636
Cow-pea	—	571
Clover	789 to 805	797
Lucerne	651 to 963	831
Grasses	—	861
Various native plants (*i.e.* weeds)	277 to 1076	—

widest range of crops, and they allow of a grouping as follows:—

1. Most economical. Millet, Maize.
2. Less economical. Barley, Oats, Potatoes, Cow-peas.
3. Least economical. Lucerne, Grasses, Flax.

[1] For a study of "Drought Resistivity" of plants see N. A. Maximov, *The Plant in Relation to Water*, Chap. 12. In discussing the effect of dryness of habitat on morphological structure he suggests that drought resistance depends, not on modifications to economise water, but on those to withstand wilting. See also F. M. Haines, *Ann. Bot.*, 1928, **42**, 823.

N. Tulaikov's experiments [1] at Saratov, Russia, gave nearly the same order :—

1. Most economical. Maize, Oats, Potatoes, Rye, Winter wheat.
2. Less economical. Barley, Spring wheat, Lucerne, Flax, Millet.
3. Least economical. Pumpkins, Cicer (chick-pea).

The most economical plants are, in general, those of short-growing period, and the less economical, those requiring longer time.

Plants differ also in the times when they need water. Spring cereals, for instance, need it in the early weeks of life : if they do not get it, they die. Winter sown cereals, on the other hand, are less dependent on spring rainfall, so also are certain fodder crops.

Water Requirements of Plants : Influence of other Factors.

(*a*) *Temperature and Rainfall.*—For the same variety of the same crop the transpiration coefficient usually increases with the temperature and the water supply : the relation to rainfall is complicated by the fact that high rainfall, which increases the water consumption, may mean low temperature which decreases it. In Tulaikov's experiments at Besentchuck, Samara, the coefficient was low in the wet seasons and high in the dry ones :—[2]

	1911.	1912.	1913.	1914.
Character of season .	Very dry	Average	Very wet	Rather dry
Wheat, var. Polltawka	628·4	444·5	338·6	387·6
,, ,, Bieloturka	576·3	475·9	316·5	397·1
Oats ,, Giant .	655·1	510·3	347·4	369·9
Barley ,, Moravian .	617·9	461·6	230·3	413·3

[1] *J. Agric. Sci.*, 1929, **19**, 1.

[2] *Journ. Opitnoï Agronomii*, 1915, **16**, 36, 37. Abs. in *Int. Inst.*, Rome, *Bull. Agric. Intell. and Plant Diseases*, 1915, **6**, 813.

(*b*) *Nutrient Supply.*—Increases in nutrient supply reduce the transpiration ratio. This was shown for cereal crops by von Seelhorst at Göttingen and for sugar beets at Bernburg, the station founded in 1882 under the directorship of Hellriegel expressly for the study of this crop. The results of Wilfarth's pot experiments [1] supplying various amounts of nitrate are given in Table 7.

TABLE 7.—EFFECT OF VARYING FOOD SUPPLY ON THE WATER REQUIREMENTS OF SUGAR BEET. WILFARTH.

Nitrogen supplied, grams	·42	1·26	2·10	2·94	3·36	3·78
Weight of dry matter produced, grams	23·0	73·9	96·5	132·4	167·6	188·8
Water transpired, grams	13,100	34,570	39,420	55·190	62,600	72,280
Stated as inches of rain	3·6	9·4	10·7	15·8	17·0	19·6
Water used per gram of dry matter formed	569	468	409	417	374	383

Later investigations show that the effect is partly due to the increased plant material produced by a given area of leaf under adequate nutrient supply, resulting in a lower ratio of leaf weight and therefore of transpiring area to total weight of plant; partly also to an actual reduction in transpiration per unit area of leaf.[2] In field soils the effect varies with the need for the nutrient; Arland showed that nutrients reduced the transpiration ratio of oats only when they increased the yield, and indeed he suggests that this ratio might afford a useful index of fertiliser deficiencies (Table 8).

Relation to Irrigation Practice.—These investigations into the transpiration ratios find useful application both in dry regions and in irrigated regions. Economical use of water is essential: excessive consumption not only takes water that might advantageously be used elsewhere; it also has injurious

[1] *Bied. Zentr.*, 1905, **34**, 167.

[2] L. A. T. Ballard, *Aust. J. Expt. Biol.*, 1933, **11**, 161; R. F. Williams, *ibid.*, 1935, **13**, 49.

TABLE 8.—TRANSPIRATION RATIOS AND YIELDS OF OATS AS AFFECTED BY MANURING. A. ARLAND.[1]

	Clay Soil.		Sandy Soil.	
	Yield of Oats, gm. (Air Dry).	Transpiration Ratio.	Yield of Oats, gm. (Air Dry).	Transpiration Ratio.
Complete fertiliser.	123	173	149	178
No potash (NP) .	123	176	140	192
No phosphate (NK)	42	319	133	133
No nitrogen (PK) .	43	265	36	299
No manure . .	33	340	34	332

effects on the soil (p. 322). Cultivators almost invariably tend to take too much water, with loss to themselves and to others on the same irrigation system.

EFFECTS OF WATER SUPPLY ON THE HABIT OF GROWTH AND THE COMPOSITION OF THE PLANT.

The water supply to the plant must be continuous. Any shortage, even for a brief period, causes wilting, and if it is sufficiently intense it permanently affects growth. Shortage in early days causes a retardation in growth that may continue throughout the plant's life ; shortage later on may induce premature ripening and cause the seed to be small and abnormal in character.

Differences in level of supply, each level being fairly constant, cause definite changes in the plant. A low level of water supply induces the formation of small glaucous leaves and a tendency to early seed formation ; these characteristics are well shown by the vegetation of dry sandy soils.

As the water supply increases the root system increases both in extent and in fineness, the leaves become larger and greener. With further supplies the root system becomes more restricted and less fibrous, while the leaves continue to become larger : this difference in behaviour between roots and leaves

[1] A. Arland, *Ztschr. Pflanz. Düng.*, 1933, A, **28**, 172.

continues with increasing water supply, till finally the root system is reduced to a few stout roots only. Experimental studies of the changes in character of the root system were made by von Seelhorst (1898-1911), while extensive field observations are recorded by J. E. Weaver.[1]

The osmotic pressure of the cell sap in the roots of plants is influenced by the degree of wetness of the soil. Iljin, Nazarova, and Ostrovskaja[2] found values between 5 and 7 atmospheres for plants growing in swamps and between 19 and 22 atmospheres on the steppes, where the moisture content was presumably not much above the wilting coefficient (p. 493). Higher values are developed in saline soils.[3] The osmotic pressure in the leaves is usually greater than that in the roots. The ratio depends on the nature and size of the plant and the environmental conditions.

The effect of varying water supply on the chemical composition of the plant has been studied by the sugar beet workers in Europe and the irrigation workers in the British Empire and the United States.

As the water supply increases the absorption of mineral matter, especially of calcium,[4] increases also, as shown in Table 9. On the other hand, the absorption of nitrogen does not increase so much, if at all, as the water supply increases, probably because the nitrate is more readily leached out than the other constituents. In so far as the amount of growth increases with increasing water supply the percentage of nitrogen decreases (see Fig. 8, p. 72).

The effect of water supply on maturation is very marked. As the water increases the amount of leaf increases more than that of seed: thus for cereals the ratio of grain to straw de-

[1] *Root Development of Field Crops.* McGraw-Hill, 1926.
[2] *Journal of Ecology,* 1916, 4, p. 160.
[3] T. G. Hill, *New Phytol.,* 1908, 7, 133.
[4] The Bernburg pot experiments with sugar beet gave similar results, *Mitt. Anhalt. Ver.-Sta. Bernburg,* 1927, No. 63, p. 70. B. W. Doak, however, found a lower percentage of calcium in lucerne in a moist than in a dry season (*N.Z. J. Sci. Tech.,* 1929, 11, 108).

creases when the water supply becomes large (Table 5, p. 34). This ratio is of great importance to the agriculturist. In dry conditions, also, ripening comes quickly, and this reduces the yield and affects the composition, as shown later. Indeed, ripening is more profoundly influenced by water supply than by any other factor except temperature.

TABLE 9.—PERCENTAGES OF NITROGEN, ASH, PHOSPHORUS, POTASSIUM, CALCIUM, AND MAGNESIUM IN WHEAT GRAIN GROWN UNDER IRRIGATION. J. E. GREAVES AND E. G. CARTER.[1]

Amount of Irrigation Water.	Calcium.		Magnesium.		Nitrogen.		Ash.		Phosphorus.		Potassium.	
	Per Cent.	lb. per Acre.	Per Cent.	lb. per Acre.	Per Cent.	lb. per Acre.	Per Cent.	lb. per Acre.	Per Cent.	lb. per Acre.	Per Cent.	lb. per Acre.
None . .	0·103	2·31	0·170	3·82	2·39	53·82	1·56	35·12	0·295	6·64	0·396	8·92
5 ins. .	0·107	2·02	0·171	3·54	2·16	44·88	1·56	34·17	0·301	6·38	0·414	8·97
10 ,, .	0·122	2·63	0·172	3·65	2·18	47·14	1·57	35·90	0·306	6·38	0·439	9·49
15 ,, .	0·165	3·53	0·172	3·23	1·99	42·38	1·71	36·38	0·323	6·87	0·491	10·47
20 ,, .	0·195	3·78	0·198	3·77	1·98	37·75	2·01	38·45	0·371	7·08	0·490	9·35
35 ,, .	0·211	4·72	0·207	4·64	2·01	45·12	2·28	51·13	0·458	10·24	0·534	11·95
67·5 ,, .	0·262	5·64	0·224	4·80	2·06	44·70	2·19	47·13	0·424	9·12	0·535	11·50

Many other properties of the plant are altered by variations in water supply, especially those related to the odours, and the so-called "active principles" such as glucosides, alkaloids, etc. In many instances the percentages of these substances are decreased when the water supply is increased.

Grain Crops.—The water supply reacts on the composition of the grain by inducing changes in the composition of the plant during the time of translocation, and by affecting the length of the translocation process from the first laying down of the endosperm cells to the completion of ripening. In dry conditions the higher percentage of nitrogen in the plant tends to raise the percentage of nitrogen in the grain.

This result is of special interest for wheat and barley, for both of which nitrogen content affects the market value: high

[1] *J. Biol. Chem.*, 1923, **58**, 531-541. See also J. E. Greaves and D. H. Nelson, *J. Agric. Res.*, 1925, **31**, 183-189.

nitrogen content being desired for wheat [1] and low nitrogen content for barley. General field experience shows, in accordance with the rule, that wheat grown in dry regions is richer in nitrogen than wheat grown in wet ones: thus in C. H. Bailey's examination of the data for spring wheat gathered in sixteen counties in Minnesota [2] the results were:—

Rainfall: Apr. 1-Sept. 1, inches	12-14	14-16	16-18	18-20	20-22	22-24
Nitrogen per cent. in grain	2·62	2·41	2·14	2·35	2·26	2·04

F. T. Shutt,[3] comparing wheat grown under irrigation at Invermere, D.C., and on dry land at Lethbridge, Alta, obtained the following percentages of "protein":—

	1st Year.	2nd Year.	3rd Year.
Irrigated	14·02	16·93	13·91
Dry land	16·70	18·47	18·18

The percentage of nitrogen in barley grain is in like manner reduced by rain falling in the growing season; indeed the

[1] This is an important factor in determining the difference in market price between Canadian and English wheat. Some recent average analyses have been—

	Canadian.	English.
Per cent. of moisture	10-14	16-18
Per cent. of nitrogen in fresh grain	1·8-2·4	1·45-2·2
(protein is estimated as N × 5·7)	Modal value 2·1	Modal value 1·6
	On dry grain 2·4	On dry grain 1·9

The "quality" of the gluten, however, has to be taken into account; a wheat may have a high nitrogen content and a poor baking value, if the gluten be of poor "quality."

[2] *Minn. Agric. Expt. Sta. Bull.* No. 131, 1913.

[3] F. T. Shutt, *Trans. Roy. Soc. Canada*, 1935, **29**, § 3, pp. 37-39.

connection is so close that a reasonable forecast of the nitrogen content can be based on a knowledge of the rainfall.[1]

Air Supply.[2]

It is well known among farmers and gardeners that soil aeration is essential to fertility, but exact measurements are difficult to obtain. The phenomena are more complex than appears at first sight, involving two wholly distinct factors :—

1. The necessity of a supply of oxygen to the plant root.
2. The toxic effect of the carbon dioxide which invariably accumulates in a non-aerated soil or other medium.

Plants vary considerably in their sensitiveness to these factors. They do not all stand in equal need of oxygen for their roots. E. E. Free [3] grew buckwheat in water cultures, blowing air through one set, and nitrogen, oxygen, and carbon dioxide respectively through others. The plants supplied with nitrogen were indistinguishable from those supplied with air or oxygen : they all grew normally to maturity. Buckwheat roots, therefore, apparently need but little gaseous oxygen. When, however, carbon dioxide was given, the plants sickened and wilted within a few hours and died in a few days. Barley, on the other hand, is more sensitive to deficient oxygen supply.

Stiles and Jørgensen [4] have confirmed this difference between barley and buckwheat.

Soil experiments lead to similar results, though they are more difficult to carry out. B. E. Livingston and E. E. Free [5]

[1] *Fifty Years of Field Experiments at the Woburn Experimental Station*, by E. J. Russell and J. A. Voelcker, with a Statistical Report by W. G. Cochran (Rothamsted Monographs, 1936).

[2] For an extensive bibliography see *Aeration and Air Content*, F. E. Clements, *Carnegie Pub.*, No. 315, 1921, and for more recent papers W. F. Loehwing, *Plant Physiol.*, 1934, **9**, 567.

[3] Johns Hopkins Univ. Circular, 1917, 198.

[4] *New Phytol.*, 1917, **16**, 181.

[5] Johns Hopkins Univ. Circular, 1917, 182.

showed that different plants varied in their susceptibility to the exclusion of oxygen; *Coleus blumei* and *Heliotropium peruvianum* were the most sensitive, the intake of water in their roots ceasing within twelve to twenty-four hours owing to death of the roots, and the entire plants ultimately died when oxygen was replaced by nitrogen.

The extended investigation of Cannon [1] indicate two "cardinal concentrations" of oxygen in the soil air: a lower one beyond which the roots cease to grow, and an upper one at which growth is normal and beyond which further additions of oxygen have no effect; indeed, much more oxygen may do harm.[2] The concentrations differ with different plants; some, such as rice and certain of the *Salix* family, can continue root growth when the percentage of oxygen is as low as 0·5; others, such as maize and peas, need much more, indeed, for full growth, the 20·97 per cent. of ordinary air is not enough. Even for the same plant the values are not constant but vary with the temperature, being lower at low temperatures than at higher ones, apparently because water has greater power of dissolving oxygen at lower temperatures. The values also depend on the diluting gas, being considerably lowered by the substitution of helium for nitrogen, oxygen diffusing so much more rapidly through helium.[3]

Loehwing [4] has shown that continuous aeration of the sand or soil cultures of sunflowers and soya beans led to the development of a large root system, more fibrous and branching, with thicker cell walls and more reserve carbohydrate; the uptake of minerals increased. The tops were larger, more vigorous and the leaves were darker green in colour. Root aeration is particularly important during the re-

[1] *Carnegie Instn. Pub.*, No. 368, 1925.

[2] Even the normal concentration of oxygen is above the optimum for the germination of some seeds (T. Morinaga, *Boyce Thompson Instit. Contr.*, 1926, 1, 100).

[3] E. E. Free in *Carnegie Inst. Pub.*, No. 368, 1925.

[4] *Plant Physiol.*, 1934, 9, 567.

productive phase, and favours the setting and development of fruit.[1]

Root respiration is closely connected with uptake of water and of nutrients. Leta Henderson [2] showed that the curves for CO_2 evolution and water absorption by the roots in distilled water or in culture solution were parallel, and Loehwing showed that, with fuller aeration, the nutrients were more rapidly taken up; the initial absorption of potassium and magnesium was much accelerated, while the absorption of calcium and phosphorus, though less accelerated, continued longer, and the final percentages of calcium, phosphorus, potassium and total ash were increased.

Some physiologists, indeed, even regard root respiration as being causally related to the uptake of nutrients. Brooks and Briggs [3] have sketched out a respiration mechanism involving an exchange of hydrogen and bicarbonate ions from the plants' cells for anions and cations entering from the soil. Osterhout [4] and his school consider that the entry of nutrients is dependent on a gradient of acidity between the vacuole and the external solution, and that this gradient is in turn determined by the respiration rate. Models have been set up to demonstrate the dependence of the rate of absorption of nutrients on the rate at which CO_2 is bubbled through the solution. Lundegårdh and Burström suppose that respiration is causally related to anion but not cation absorption, and that it is absorption that governs respiration rather than the converse.[5]

[1] See also W. B. Albert and G. M. Armstrong, *Plant Physiol.*, 1931, **6**, 585, for cotton; W. F. Bewley, *Cheshunt Station Rept.*, 1921, **7**, 10-13, for tomatoes; and R. S. Hole and P. Singh, *Indian Forest Rec.*, 1916, **5**, Pt. IV, 43, for sal.

[2] Leta Henderson, *Plant Physiol.*, 1934, **9**, 283-300. See also N. Potapov and N. Stankov, *C.R. Acad. Sci. (U.S.S.R.)*, 1934, for a study of periodicity. The two processes, root respiration and absorption of nitrate and phosphate, simultaneously attain a maximum during the night.

[3] S. C. Brooks, *Protoplasma*, 1929, **8**, 389; G. E. Briggs, *Proc. Roy. Soc.*, B, 1930, **107**, 248.

[4] W. J. V. Osterhout, *Biol. Rev.*, 1931, **6**, 369; *Ergeb. Physiol.*, 1933, **35**, 967, and elsewhere.

[5] H. Lundegårdh and H. Burström, *Biochem. Ztschr.*, 1933, **261**, 235.

Seeds and roots differ also in their behaviour to carbon dioxide, the effects depending on the stage of growth. Germination of all seeds is retarded or inhibited so long as sufficient carbon dioxide is present, but some seeds, *e.g.* peas, beans, cabbage, barley, and onions, germinate soon after its removal, while others, such as charlock (*Brassica alba*), do not. Kidd [1] has shown that the seeds in this latter group behave as if narcotised by the carbon dioxide and will not germinate until they have been thoroughly dried and rewetted. He thus explains the remarkable appearance of charlock in English crops after a deeper ploughing than usual, in circumstances suggesting that its seed had lain buried for many years without losing its viability.[2]

The growing plant is much affected by carbon dioxide in the soil air in excess of the normal amounts. Stoklasa and Ernest [3] and Lundegårdh [4] found that 1 per cent. of CO_2 in the soil atmosphere 15 cms. below the surface retarded growth and was sometimes very harmful.

This is in contradistinction to the leaves which may benefit by increasing CO_2 concentration of the atmosphere up to a certain point.

In field conditions it is not usually possible to distinguish between the two factors of oxygen deficiency and carbon dioxide poisoning. The total effect on the growing plant is shown in the experiments of Hall, Brenchley, and Underwood (1913) with lupins grown in various materials. Root development was good in those allowing easy diffusion of air; it was less where diffusion was more difficult. The yields were :—

[1] *Proc. Roy. Soc.*, 1914, B, **87**, 408, 609; 1916, B, **89**, 136; with C. West, *Ann. Bot.*, 1917, **31**, 457.

[2] Direct experiments by W. E. Brenchley showed the presence of viable seeds of *Atriplex patula, Polygonum aviculare, Veronica Tournefortii*, and other arable weeds, but not of charlock, at a depth of 5 inches below the surface of soil that had been laid down to grass for sixty years (*Journ. Agric. Sci.*, 1918, **9**, 1-31). See also H. G. Chippindale and W. E. J. Milton, *J. Ecology*, 1934, **22**, 508.

[3] *Centr. Bakt. Par.*, Abt. II, 1905, **14**, 723.

[4] *Soil Sci.*, 1927, **23**, 417, and *Central. anstalt. försöksväs jordbruk*, 1928, No. 331.

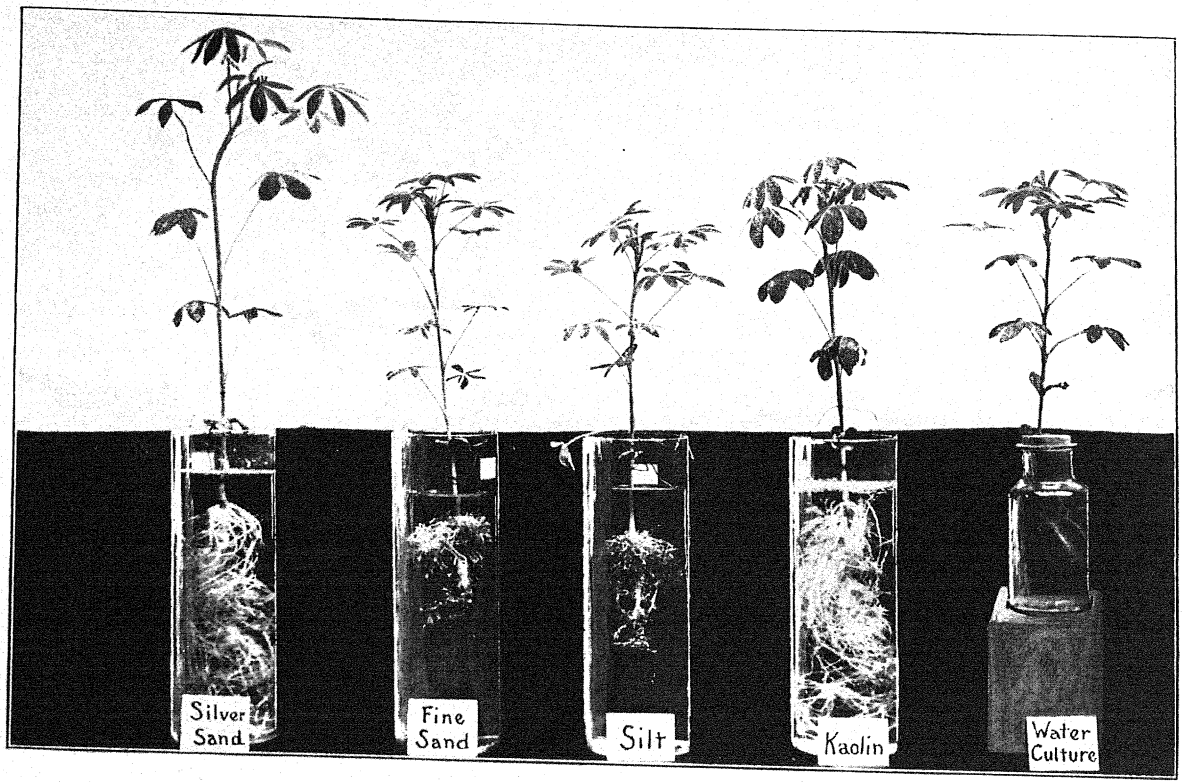


FIG. 5.—Influence of medium on root development of lupines.
(Hall, Brenchley and Underwood)

	Weight of Dry Matter Formed, Grams.
Material allowing diffusion of air : Coarse sand	2·474
,, ,, ,, ,, Kaolin .	1·833
Material allowing less diffusion of air : Fine sand	1·131
,, ,, ,, ,, Silt. .	1·393
,, ,, ,, ,, Water .	0·942

The results are illustrated in Fig. 5.[1] The harmful effect of restricted air supply to the roots becomes very marked when soil is water-logged, and may lead to cessation of growth, to disease, or even to the death of the plant. Nearly fifty years ago Sorauer showed [2] how deficient root aeration may bring on plant diseases : Warming (1909) has discussed its ecological significance. Lawrence Balls [3] has adduced evidence to show that the growth of the cotton plant in Egypt is stopped and the roots killed when the water rises in the soil : as the

TABLE 10.—EFFECT OF IMPROVING DRAINAGE IN IMPROVING YIELD OF CROPS. A. AND G. L. C. HOWARD, INDIA.[4]

Drainage of Plots.	Yield of Cotton, lb. per Acre.	Wheat, lb. per Acre.
Very bad . . .	145	370
Fair to good . .	366	600
Very good . . .	510	1005

[1] For other papers see C. A. Shull, *Bot. Gaz.*, 1911, **52**, 453-477, and W. A. Cannon and E. E. Free, *Science*, 1917, **45**, 178-180.

[2] *Handbuch der Pflanzenkrankheiten*, successive editions, 1879 *to present time.* U. Brizi (*Ann. Inst. Agrar.*, Milan, 1905, **6**, 84) traced the *Brusone* disease of paddy rice to lack of aeration of the roots and showed that it did not occur if algæ are present.

[3] " The Spacing Experiment with Egyptian Cotton," *Phil. Trans. B*, 1915, **206**, 103 ; " The Sowing-date Experiment with Egyptian Cotton," *Phil. Trans. B*, 1915, **206**, 403 ; " The Influence of Natural Environmental Factors upon the Yield of Cotton," *Phil. Trans. B*, 1918, **208**, 157. See also J. Templeton, " Some Observations on the Behaviour of Cotton Roots in Deep Soil," *Proc. 5th Internat. Bot. Cong.*, Cambridge, 1930, p. 453.

[4] *Application of Science to Crop Production*, 1929, p. 35.

water falls, however, young roots are sent out again. A. and G. L. C. Howard in India have shown that deficient soil aeration leads to the serious indigo wilt. Improved aeration eliminated the disease and increased the yield. Some of their results with other crops are given in Table 10.

Temperature.

It is difficult to separate soil temperature effects from temperature effects in general, and in practice the distinction is unnecessary since the temperature of the air is largely determined by that of the soil.

The temperature at the time of sowing profoundly affects the subsequent history of cereal plants. These plants exist in two well-defined forms, summer and winter: the summer forms are invariably sown in spring and the winter forms in autumn. If the times are reversed and winter varieties are sown in spring after the frosts have ceased, they produce no ears during the current season, but only in the following season. The phenomena have been studied in detail by Gassner [1] and by Maximov.[2] Gassner has shown that the result is attributable to the temperature of germination. For winter cereals the optimum temperature of germination for ear production is 0° C.; the limit is somewhere about 5° C.; plants grown from seed germinated above 5° C. and not allowed during growth to fall below this temperature do not form ears but grow vegetatively only. If, however, at any time during growth they are cooled to 0° C., and kept cool sufficiently long, they form ears normally.

The summer varieties do not behave like this: they produce ears whatever the temperature of germination so long as it is not too high.

Maximov has obtained intermediate forms which are summer varieties in the sense that they produce ears in the current year if sown in spring, but produce them earlier if

[1] G. Gassner, *Zeit. Bot.*, 1918, **10**, 417-430.
[2] N. A. Maximov, *Biol. Zentralbl.*, 1929, **49**, 513-543.

they are germinated at lower temperatures. These effects of temperature of germination on the subsequent growth of plants have been utilised by T. D. Lyssenko in devising a new method called Jarowisation or Vernalisation for the growth of crops.[1]

In Holland much work has been done showing that the time of flowering of bulbs is dependent on the temperature of storing the bulb : low temperature storage being conducive to early flowering.[2]

Temperature affects the rate of growth of plants, and thus determines what plants can be grown and what cannot be grown in a given area.

If the temperature is too low a yellow or purplish colour may appear in the leaf, and the plant grows so slowly that it is liable in its early stages to succumb to insect pests, such as wireworms, and in its later stages to be cut down by autumn frosts before it has time to ripen. As the temperature rises the plant makes greater growth and becomes taller ; then, with further rise of temperature beyond a certain point which depends on the intensity of the light, the plant is stunted, less robust, and, when much water is also supplied, liable to fungoid pests that prove very troublesome in commercial glasshouses. The optimum temperature range is higher for the growing plant than for the seedling, and it is highest for the period of maturation.

Broadly speaking, roots flourish best at a lower temperature than the shoots, and they suffer considerably if the temperature rises too high. W. E. Brenchley[3] records some striking examples of injury, and even death, from high root temperatures in water cultures. High temperatures are tolerated

[1] For a summary of this interesting method see Vernalisation, *Imp. Bur. Plant Genetics Bull.* No. 17, 1935 ; also J. R. Thomson, *Sci. Prog.*, 1936, p. 644.

[2] E. van Slogteren, *Wetensch. Onderzoek Blombollencultur*, 1917-1935, Lisse.

[3] W. E. Brenchley, *Ann. Appl. Biol.*, 1920, **6**, 211-244 ; W. E. Brenchley and Kharak Singh, *ibid.*, 1922, **9**, 197-209.

provided they do not last too long and provided also that they are followed by sufficiently low temperatures. Fluctuating temperatures proved better than steady ones.[1] In the Wisconsin experiments with potatoes grown under different soil temperatures the highest yield of tubers was obtained at 18° C. but the tops grew best at 21° C.[2] At higher temperatures the rate of respiration of the leaves was so high that no carbohydrate was available for tuber formation and at 29° C. this ceased altogether.[3]

L. R. Jones, J. Johnson, and J. G. Dickson [4] give some good pictures showing the effect of temperature on root growth of wheat and of maize, bringing out the fact that wheat has its optimum temperature for root growth at 16° C. and maize at 28° C., at which temperature wheat roots are severely curtailed. The investigation was concerned chiefly with the relationship of soil temperature to plant disease: the optimum range of temperature for the disease is not necessarily the same as that for the host plant, so that a crop may be much more susceptible in one set of temperature conditions than in another.

W. A. Cannon [5] has studied the influence of soil temperature on the roots of desert plants, and in summarising his general experience he suggests that roots which penetrate deeply and ordinarily grow on fine textured soils are less responsive than surface roots to changes in temperature and aeration.

[1] F. G. Gregory, *Ann. Bot.*, 1926, **40**, 1.

[2] L. R. Jones, H. H. McKinney, and H. Fellows, *Wis. Agric. Expt. Sta. Res. Bull.* No. 53, 1922.

[3] J. Bushnell, *Minn. Agric. Expt. Sta. Tech. Bull.* No. 34, 1925.

[4] *Wis. Agric. Expt. Sta. Res. Bull.* No. 71, 1926.

[5] W. A. Cannon, *Amer. J. Bot.*, 1915, **2**, 211-224; *Carnegie Instn. Yrbk.*, 1917, pp. 91-92, and 1918, pp. 83-85; see also *Science*, 1923, **58**, 331-332.

Climatic Factors.

Water supply and temperature are the two chief factors determining the distribution of crops. In the warm, dry, eastern counties of Great Britain crops are grown for seed; great quantities of wheat and barley are grown in Norfolk, Suffolk, and the Isle of Thanet; mangold seed and turnip seed is produced in East Kent. Wetter districts are more favourable for swedes and oats; very wet districts for grass. The warm, moist, south-west of Cornwall is very favourable for early vegetables, cabbage, cauliflower, etc., whilst the cooler Lincolnshire and Cheshire are well suited to potatoes. It is possible by suitable operations to modify somewhat both the temperature and the water content of the soil, and so to make the soil conditions rather more favourable for any particular crop.

Some interesting results are obtained in glass-house practice. Tomato growers have learned to regulate water supply and temperature in such a way as to produce compact bushy plants, which they know by experience give more fruit than the softer, larger plants obtainable under other conditions. Until the blossom is fertilised or has "set," therefore, vigorous growth is not encouraged, and, in many cases, while the atmosphere is artificially damped, water is actually withheld from the roots until, in the picturesque language of the grower, "the plants cry for it." After "setting," water is liberally supplied and top dressings of manure are given.

R. A. Fisher and his colleagues have studied by statistical methods the effect of rainfall and hours of sunshine on the yields of crops at Rothamsted and Woburn, and F. G. Gregory has used growth rates successfully in studying the influence of climate on the growth of barley.[1]

Gregory brings out the important point that the different physiological processes making up plant growth are differently affected by changes in external conditions and thus tend to

[1] *Ann. Bot.*, 1926, **40**, 1.

compensate one another so that the total change in growth is less than might be expected. Thus assimilation per unit area of leaf (net assimilation rate) increases or is positively correlated with increasing temperature and radiation up to a point, while rate of growth of leaf area is negatively correlated with radiation. In sunny weather the assimilation is good, but the leaf growth is poor ; in cold dull weather the assimilation is less, but the leaf growth is better ; variations in temperature and light intensity, therefore, make less difference than might be expected.[1]

Light.

Although light is not a soil factor it nevertheless indirectly affects the soil by modifying the flora which, as we shall subsequently see, largely determines the nature and amount of the organic matter of the soil. Tall vegetation keeps off light from the lower growing plants and more or less suppresses them. Thus on the Rothamsted grass plots clover is seriously reduced in amount by nitrate of soda which causes tall growing grasses to flourish : *Lathyrus*, on the other hand, in consequence of its tall growing habit is not adversely affected but grows vigorously. Numerous other instances are recorded in the *Journal of Ecology*.[2] The extreme case is seen in woodland where there is very little undergrowth and where, therefore, organic matter has not accumulated in the soil. Adjacent pieces of land at Rothamsted, both untreated and differing only in the flora, showed the differences in composition recorded in Table II.

One of the most effective ways of suppressing weeds is to grow a heavy crop which, in the farmer's language, " smothers " them by excluding light and by exerting certain

[1] For other examples of the relation between meteorological conditions and crop growth, including the incidence of diseases, see Report of Conference of Empire Meteorologists, Ministry of Agriculture, 1929.

[2] See *e.g.* E. P. Farrow, *Journ. Ecology*, 1916, **4**, 57, and E. J. Salisbury, *ibid.*, 1929, **17**, 197.

TABLE II.—EFFECT OF VEGETATION TYPE ON SOIL COMPOSITION.

	Long Established.		Established 40 Years.	
	Open Land. Flora of Grass and Clover.	Wood-land. No Green Plants.	Open Land. Flora of Grass and Clover.	Wood-land. No Green Plants.
Organic matter—				
0— 9 ins. . .	8·5	6·7	7·9	8·1
9—18 ,, . .	4·8	4·8	6·7	5·2
Nitrogen—				
0— 9 ins. . .	0·256	0·185	0·182	0·173
9—18 ,, . .	0·097	0·093	0·084	0·081

root effects. Strong radiation, on the other hand, tends to inhibit leaf growth quite apart from any effect of high temperature, with which it is associated.[1] This may be an important factor in restricting the vegetation in open country in the tropics as compared with the more extensive flora of the wooded and shaded areas.

Food.

The nutrition of plants is complicated by the fact that plants synthesise their own food from various substances taken out of the air and the soil. It is common in farmers' lectures to speak of these as the actual foods: in reality they are only the raw materials out of which the food is made. It is convenient to make a distinction between the elements necessary in large quantities, and those of which mere traces suffice: the effect of the former can readily be demonstrated in water and sand cultures; the latter are more difficult to study, as traces are always present in the seed, and often also in the nutritive medium, or the vessel in which the plant is grown.

The substances needed in quantity are carbon dioxide, water, oxygen, and suitable compounds of nitrogen, phosphorus, sulphur, potassium, calcium and magnesium. Of

[1] F. G. Gregory, *Ann. Bot.*, 1921, **35**, 93; 1926, **40**, 1.

these nitrogen, phosphorus, and potassium compounds are required in such large amounts that they usually have to be added to soils as artificial fertilisers in order to obtain maximum yields in agricultural practice. The other nutrient elements are generally present in air, in soils or in rain, in sufficient amounts to exert their full effect, though cases are recorded where crops have responded to additional supplies of sulphates, iron and magnesium. The function of these nutrients is to build up the plant substances.

Certain other substances are needed in small amounts only. These have been studied at the Institut Pasteur, notably by Mazé and by Gabriel Bertrand. Mazé (1919) showed that the ordinary culture solution was much improved as a medium for the growth of maize by the addition of small quantities of numerous other elements. This has been confirmed by D. R. Hoagland and W. C. Snyder [1] who made up a solution containing twenty-six supplementary elements which produced better and healthier strawberry plants than one containing twelve only. A large number of investigations followed Bertrand and Mazé's work. The elements proved to be essential are iron, manganese, and, for certain crops, boron. Others probably always present in the plant are fluorine, iodine, chlorine, copper, aluminium, zinc, cobalt, and nickel; it is not known whether they serve some useful purpose or have simply been absorbed along with the nutrients proper. The elements of this group apparently serve three purposes which, however, may often be closely connected :—

1. Catalytic, the promotion of oxidation or other essential reactions.

2. Stimulative, the setting in train of differentiations or other processes vitally important to the plant.

3. Prophylactic, protecting the plant against disease.

[1] *Proc. Amer. Soc. Hort. Sci.*, 1933, **30**, 288. Hoagland and Snyder picturesquely describe these complex media as " A to Z solutions " ; their effectiveness is confirmed by W. Schropp and K. Scharrer, *Jahrb. Wiss. Bot.*, 1933, **78**, 544.

The catalytic elements probably include iron, which is essential to the formation of chlorophyll; and manganese, apparently needed for the activation of oxidases or otherwise for oxidations in the plant. The stimulative elements probably include boron, needed to stimulate the formation of the branch system of circulatory vessels that links up the nodules on the roots of leguminous plants with the main system. The prophylactic elements include boron, copper, and zinc.

Between beneficial effects and toxicity the margin appears to be narrow, and almost all the elements essential to plant nutrition are capable of producing toxic effects under other conditions. In the case of the major nutritive elements toxicity occurs only when a sufficiently large excess is present to alter considerably the osmotic relationships or the proper physiological balance of the nutrient medium: the transition from beneficial to harmful effects is very gradual. In the case of elements of which only small amounts are needed the transition is much sharper: the limits are easily overstepped and toxic effects set in when the minute beneficial amount is exceeded.

Group I. Elements needed in relatively large amounts to Build Up the Plant Tissues.

Carbon.

It is generally assumed that plants derive all their carbon from the air, but the French investigators have persistently held the view that some may come from the soil (p. 16). Livingston and Beall have argued [1] that the plant derives some of its carbon, in suitable circumstances possibly as much as 5 per cent., from the carbon dioxide dissolved in the soil moisture and transported to the leaves in the transpiration stream. A good deal of physiological work has been done in water cultures. Knudson [2] finds that saccharose, glucose,

[1] B. E. Livingston and R. Beall, *Plant Physiol.*, 1934, **9**, 237.
[2] Cornell Repts. (Ithaca, N.Y.), Pt. 1, 1917, 747 (Memoir 9 of 1916).

maltose, and fructose are directly absorbed and utilised by green maize, Canada field pea, timothy, radish, vetch, etc., giving rise to a characteristic branched root system. While these substances do not occur in the soil other soluble carbon compounds are present, especially in glass-house soils, and may exert important effects.

There is considerable evidence, however, that by far the larger portion of the carbon of the plant is taken up from the atmosphere and not from the soil, but the phenomena are not wholly independent of the soil. The amount of carbon dioxide in the atmosphere is subject to slight variations which may arise from variations in biochemical activity in the soil, and may be a factor of importance in crop production. Brown and Escombe [1] found that the amount varied at Kew from 2·43 to 3·60 [2] volumes per 10,000 volumes of air, the average being 2·94. Taking the month of July as an example, the average values were :—

	1898.	1899.	1900.	1901
CO_2 in 10,000 volumes of air .	2·83	2·88	2·86	3·11

Increases in the amount of carbon dioxide in the air cause increases in plant growth.[3] Attempts have been made to apply this fact in glass-house practice, special stoves being used to generate the carbon dioxide; they are not yet, however, commercially successful.[4]

[1] *Proc. Roy. Soc.*, 1905, **76**, 118.

[2] Only on one occasion was so high a number obtained.

[3] U. Kreusler, *Landw. Jahrb.*, 1885, **14**, 913; E. Demoussy, *Compt. Rend.*, 1903, **136**, 325; 1904, **139**, 883, and many subsequent workers, the most recent being B. D. Bolas and F. Y. Henderson, *Annals of Botany*, 1928, **42**, 509. For a full discussion see H. Lundegårdh, *Der Kreislauf der Kohlensäure in der Natur*, Jena, 1924, also *Soil Sci.*, 1927, **23**, 417, where he shows a striking parallelism between soil respiration and crop yield.

[4] O. Owen, T. Small, and P. H. Williams, *Ann. Applied Biol.*, 1926, **13**, 560; T. Small and H. L. White, *ibid.*, 1930, **17**, 81. For a good summary see *Int. Review Sci. and Practice of Agric.*, Rome, 1927, **18** 39.

Other Elements, Derived from the Soil.

The other elements derived from the soil enter the plant in solution but by processes which are quite distinct from transpiration. The elements enter at rates and during periods which vary with the plants and conditions of growth. The phenomena are illustrated by Richardson and Trumble's experiments on barley at the Waite Institute, Adelaide [1] (Fig. 4). H. Wagner [2] made a number of pot experiments with various crops harvested at weekly intervals to determine the rate of uptake of the different elements, and F. Knowles and J. E. Watkin have similarly studied wheat growing in the field (Table 12).

TABLE 12.—PRODUCTION OF DRY MATTER, AND ASSIMILATION OF NUTRIENTS FROM THE SOIL BY WHEAT GROWING IN THE OPEN FIELD.[3]

WEIGHT IN GRAMS OF SUBSTANCES IN WHOLE WHEAT PLANT GROWN IN THE FIELD.

	Before Ear Emergence.			After Ear Emergence.					
	1st Sampling (30. iv.).	2nd Sampling (21. v.).	3rd Sampling (4. vi).	4th Sampling (18. vi.).	5th Sampling (2. vii.).	6th Sampling (16. vii.).	7th Sampling (23. vii.).	8th Sampling (30. vii.).	9th Sampling (6. viii.).
Dry matter	766	2968	6185	9513	12,267	14,354	15,062	14,728	14,211
Nitrogen	27·55	54·95	79·70	89·74	96·32	109·8	109·4	109·5	109·0
Phosphoric acid	7·41	24·03	41·23	56·05	56·76	61·94	63·74	63·71	63·94
Lime	7·18	17·93	30·32	35·90	37·44	37·09	31·98	30·75	30·24
Potash	31·42	95·09	168·1	179·3	145·7	124·1	113·7	102·9	89·68
Chlorine	5·96	15·10	24·20	28·81	33·86	30·48	27·36	23·61	19·28
Silica	16·21	86·73	194·5	267·1	326·9	426·7	440·6	447·4	441·6

Nitrogen Nutrition of Plants.

The nitrogen nutrition of the plant is complicated by the fact that nitrogen compounds readily undergo changes, both

[1] *J. Dept. Agric. S. Aust.*, 1928, **32**, 224.

[2] H. Wagner, *Ztschr. Pflanz. Düng.*, 1932, A, **25**, 48, 129, and A, **26**, 8. Oats have been studied by T. W. Fagan and J. E. Watkin, *Welsh J. Agric.*, 1931, **7**, 229; certain grasses by Fagan and W. E. J. Milton, *ibid.*, 246, and sugar beet by F. Knowles, J. E. Watkin, and F. W. F. Hendry, *J. Agric. Sci.*, 1934, **24**, 368.

[3] F. Knowles and J. E. Watkin, *J. Agric. Sci.*, 1931, **21**, 612.

in the soil and in the plant. Most of the nitrogen is assimilated by the root in simple compounds and it appears finally in the form of protein: a wide range of complex substances is therefore involved.[1]

Asparagine has been regarded by Pfeffer and Schulze as the starting-point of protein synthesis in the plant: H. T. Brown showed that it was the most effective nitrogenous nutrient for the detached embryo of barley, while nitrates, glutamic and aspartic acids and ammonium sulphate were less useful.[2] Prianischnikov, on the other hand, regards ammonia as the starting-point of protein synthesis: asparagine is in his view only the innocuous storage product of any temporary excess of ammonia which would otherwise be harmful. Pot and field experiments show, however, that nitrate is almost invariably the actual nutrient. This is absorbed by the plant, reduced first to nitrite, then to ammonia [3] which is then built up into asparagine. It seems a cumbersome procedure and raises the question, why is not ammonia better than nitrate? Prianischnikov suggests that the ammonium ion is the true nutrient, but there are difficulties in getting it into the plant. It can be supplied only as a salt, but directly it is absorbed the acidic ion makes the medium acid and therefore toxic to the plant. Sodium or calcium nitrate, on the other hand,

[1] For studies of the movements of nitrogen compounds in the plant see E. J. Maskell and T. G. Mason, *Annals of Bot.*, 1929, **43**, 205, 615; 1930, **44**, 1, 233, 657; Walter Thomas (*Pyrus malus*), *Plant Physiol.*, 1927, **2**, 245. Mrs. M. W. Onslow discusses the whole subject in *The Principles of Plant Biochemistry*, Cambridge Univ. Press, 1931. See also O. F. Curtis, *The Translocation of Solutes in Plants*. McGraw-Hill, 1935.

[2] *Trans. Guinness Lab.*, 1906, **1**, Pt. 2, 288-299. For a statement of the present position in regard to the physiological role of asparagine see A. E. Murneek, *Plant Physiol.*, 1935, **10**, 447. A large number of substances were tested by Arwid Thomson, "The Assimilation of Nitrogen from Organic Compounds," Tartu, 1931.

[3] An enzyme, reducase, capable of effecting this reduction has been discovered in plants by Sophia H. Eckerson (*Boyce Thompson Instn. Contr.*, 1932, **4**, 119). It is most active in the roots but occurs also in the leaves: its activity is increased by deficiency of nitrogen but lowered by deficiencies of other essential elements.

leaves no toxic ion behind and therefore has no harmful effect. In practice, therefore, the ammonium salt is inferior as a nutrient to the nitrate, though it would be superior if the masking effect of the accompanying acid ion could be overcome. Experiments to realise this condition have been made in three ways :—

1. Along with the ammonium salt sufficient calcium carbonate is supplied to keep the medium always neutral.

2. An ammonium salt is used having an acidic ion of minimum toxicity, *e.g.* ammonium carbonate : ammonium phosphate.[1]

3. The solution is kept dilute [2] or changed continuously so that it never has time to become acid.

Under these conditions the ammonium ion appears to be more readily assimilated than the nitrate ion. From ammonium nitrate, for instance, the ammonia is taken leaving an acid solution. The effectiveness of the ammonium relative to the nitrate ion is, however, much influenced by the cations present. It is reduced when the medium becomes acid or when the supplies of calcium, potassium, or magnesium fall off : in these circumstances the nitrate ion is the better nutrient.[3]

The ease of assimilation of ammonia depends on the rate at which it is converted into asparagine and this in turn depends on the amount of carbohydrates, the other group of substances necessary for the synthesis of protein. Plants like barley, maize, and pumpkins, relatively rich in carbohydrates, readily take up ammonia ; peas and vetches, which contain less, do so only in presence of calcium carbonate ;

[1] P. Mazé, *Ann. Inst. Pasteur*, 1900, **14**, 26 ; *C.R.*, 1898, **127**, 1031.

[2] H. G. Söderbaum, *Kgl. Landtbr. Akad. Tidskr.*, 1917, **56**, 536-560.

[3] D. Prianischnikov, *Biochem. Ztschr.*, 1929, **207**, 341 ; *Ztschr. Pflanz. Düng.*, 1933, A, **30**, 38. For a general review see A. I. Virtanen, "The Nitrogen Nutrition of Plants," *Herb. Rev.*, 1933, **1**, 88 (Imp. Bur. Plant Genetics, Aberystwyth). See also K. Pirschle, *Ber. Deut. Bot. Ges.*, 1929, **47**, 86.

lupins will not normally take it up at all excepting when the carbohydrate supply is increased by special means.

In general, assimilation of ammonia seems to proceed more easily in the early stages of the plant's life when the protein is being rapidly synthesised.[1] Farm experience shows that sulphate of ammonia is better suited to some crops, *e.g.* potatoes ; and nitrate of soda to others, including wheat, barley, rye, mangolds, sugar beet.[2] The explanation suggested is that the potato "seed" contains sufficient carbohydrate reserve to allow the ammonia to be rapidly worked up into protein, while the seeds of sugar beet and the other "nitrate" plants do not. Some of the grasses apparently take up ammonia from its salts fairly easily ; clover, on the other hand, does not, although it is not altogether intolerant of ammonia.[3] Addition of sulphate of ammonia to a mixed herbage causes the grasses to develop but not the clovers, hence these become crowded out. Sulphate of ammonia is much used for clearing clover out from lawns or greens on which it is not wanted.[4]

Ammonia is much more toxic to the cell than is nitrate ; the plant can tolerate a considerable accumulation of nitrate in its juices but not of ammonia. Unlike the animal, the plant does not easily get rid of excess of nitrogen, though there is the possibility of some excretion from the roots (p. 131).

The normal nitrogenous food of plants is, however, a nitrate and there is a close connection between the amount supplied and the amount of plant growth, which is well shown in Hellriegel and Wilfarth's (1888) experiments (p. 134). Most of the nitrogen required by the plant is absorbed in

[1] See A. C. Sessions and J. W. Shive, *Soil Sci.*, 1933, **35**, 355, and A. L. Stahl and J. W. Shive, *ibid.*, 375, 469 ; H. G. M. Jacobson and T. R. Swanbeck, *Plant Physiol.*, 1933, **8**, 340 ; C. Brioux and E. Jouis, *C.R. Acad. Agric.*, 1933, **19**, 332.

[2] See W. P. Kelley's summary of the Danish experiments, *J. Amer. Soc. Agron.*, 1933, **25**, 51.

[3] J. Caldwell and H. L. Richardson, *J. Agric. Sci.*, 1936, **26**, 263.

[4] H. L. Richardson, *ibid.*, 1934, **24**, 491 ; G. E. Blackman, *Ann. Appl. Biol.*, 1932, **19**, 204 and 443.

its early days from the soil and stored in the meristematic tissues (*i.e.* the embryonic tissues capable of further growth).

The Effect of Nitrogenous Nutrients on the Habit of Growth of the Plant.

Nitrogen starvation is characterised by stunted growth and yellowish-green or for some plants reddish-green colour of the leaf,[1] the yellowing and dying being general all over the leaf, as distinct from the effect of potash starvation where the dying is from the tip and edges inwards (p. 86). On fruit trees the leaves are shed early, the lateral buds die, leaving the shoots bare, the fruits are unusually coloured: certain apples normally green become a brilliant red, while others become very pale; the root system is reduced and becomes almost entirely fibrous.[2]

Addition of sodium or calcium nitrate to a nitrogen-starved plant causes a rapid improvement in colour and increased height of plant and growth of leaf. Gregory,[3] working with barley, has shown that only the leaf area increases and not the assimilation rate, in contradistinction to potassium, which increases the efficiency of the leaf. This increased leaf growth is of great advantage in agriculture and leads to the consumption of large quantities of nitrogenous fertilisers. In the Rothamsted experiments the increased crop given by 1 cwt. sulphate of ammonia per acre corresponds on the average to the following increases per unit weight of nitrogen added:—

[1] Due to a reduction in chlorophyll content (J. H. Gilbert, *Brit. Assoc. Repts.*, 1885, p. 970; J. D. Guthrie, *Boyce Thompson Instn. Contr.*, 1929, **2**, 222).

[2] T. Wallace, *J. Pomol. Hort. Sci.*, 1925, **4**, 117; 1930, **8**, 23. In the water culture experiments of Mihovil Gračanin (*Rad. jug. Akad. Znan. Umj.*, 1932, p. 94, Zagreb) the roots decreased in length as the nitrogen supply increased.

[3] *Ann. Bot.*, 1926, **40**, 1.

	Fresh Weight.	Dry Weight.
Potatoes, tuber .	100	21
Barley grain . .	15	13
,, straw . .	18	15
Wheat grain . .	15	13
,, straw . .	25	20

The increases vary according to the season, but the variation is much less than for potassium compounds or phosphates. The recovery of the added nitrogen is usually about 40 or 50 per cent.

Greater quantities of nitrate lead to the development of large dark green leaves which are often crinkled, soft, sappy, and liable to insect and fungus pests possibly because of the thinning of the walls or changes in tissues or in composition of the sap. C. R. Hursch [1] shows that the amount of sclerenchyma is reduced in proportion to the collenchyma in the wheat plant, thus favouring the attack of *Puccinia graminis*, the mycelium of which can develop only in the collenchyma.

The time of ripening is affected by the supply of nitrogen. Plants markedly starved of nitrogen during vegetative growth ripen more slowly than those receiving adequate but not excessive amounts. Beyond a certain point, however, further additions of nitrogen lead to a prolongation of the vegetative activities; yellowing and death of the leaves are deferred. Grain formation is not retarded, at any rate so long as sufficient potash and phosphate are given, but the plants remain green for a longer period, giving the impression of delayed ripening. On technical grounds this is a disadvantage for cereals, the longer lived straw being liable to contain too much moisture at harvest time. This difficulty could be obviated if it were possible to leave the corn standing till drying of the straw was completed, but in crop production it is not possible much to delay the harvest owing to the fear of damage by autumn frosts, so that the retardation is of great practical importance. Seed crops like barley that are cut dead ripe are not supplied

[1] *J. Agric. Res.*, 1924, **27**, 381-411.

with much nitrate, but oats, which are cut before being quite ripe, can receive larger quantities. All cereal crops, however, produce too much straw if the nitrate supply is excessive, and the straw does not commonly stand up well, but is beaten down or "lodged" by wind and rain. Swede, sugar beet, and potato crops also produce more leaf, but not proportionately more root or tuber, as the nitrogen supply increases; increased root, however, is obtained in the case of mangold. Tomatoes, again, produce too much leaf and too little fruit if they receive excess of nitrate. At the Cheshunt Experiment Station [1] the omission of nitrogen compounds from the fertiliser mixture has caused the yield of fruit to increase 11 per cent. With the variety Comet the following quantities of fruit have been obtained :—

	Lb. per Plant.				Tons[2] per Acre.				Relative Weights, Average, 1916-1919.
	1916.	1917.	1918.	1919.	1916.	1917.	1918.	1919.	
Complete artificials.	4·9	5·11	3·32	5·57	38·7	35·8	25·8	42·2	100
No nitrogen . .	5·7	5·60	3·62	5·98	45·0	39·2	28·2	47·4	111

On the other hand, crops grown solely for the sake of their leaves are wholly improved by increased nitrate supply: growers of cabbages have learned that they can not only improve the size of their crops by judicious applications of nitrates, but they can also impart the tenderness and bright green colour desired by purchasers. Unfortunately the softness of the tissues prevents the cabbage standing the rough handling of the market. These qualitative differences are of great importance in agriculture and horticulture.

Three cases are illustrated in Table 13. As the nitrogen supply is increased wheat shows increases in straw greater than those in grain; white turnips show increases in leaf greater than those in root; but mangolds show substantially the same increase both in leaf and root.

[1] Annual Reports for 1917 *et seq.* [2] 1 ton = 2240 lb.

TABLE 13.—EFFECT OF VARYING SUPPLY OF NITROGENOUS MANURE O THE GROWTH OF CROPS. ROTHAMSTED.

Nitrogen in Manure, lb. per Acre.	Wheat, 1000 lb. per Acre (1852-1864).		Nitrogen in Manure, lb. per Acre.	White Turnips, 1000 lb. per Acre (1845-1848).		Nitrogen in Manure, lb. per Acre.	Mangolds, 1000 lb. per Acre (1906-1910).	
	Grain.	Straw.		Roots.	Leaves.		Roots.	Leaves.
none	1·06	1·86	none	18·37	6·05	none	11·84	2·55
43	1·68	3·03	47	22·18	9·63	86	40·12	8·51
86	2·18	4·28	137	22·96	13·78	134	65·67	13·88
129	2·27	4·78	—	—	—	—	—	—
172	2·29	5·22	—	—	—	—	—	—

These effects are modified by the time when the nitrogenous manure is given. In D. J. Watson's experiments on wheat,[1] late dressings gave less straw than early ones and fewer ears per plant; on the other hand, the numbers of grains per ear and the weight of the individual grains both increased so that the total weight of grain was hardly affected, but the grain/straw ratio increased. A larger part of the total nitrogen assimilated by the plant from the late dressings passed to the grain, and the percentage of nitrogen in the grain was higher than for early dressings. The changes proceeded steadily: there was no evidence of breaks or critical periods.

EFFECT OF NITROGENOUS NUTRIENTS ON COMPOSITION AND QUALITY OF THE PLANT.

Within a rather wide range variations in supply of nitrogen to the plant merely alter the size of the plant without much affecting its composition; small additions of nitrogen indeed may even lower the percentage of nitrogen in the final produce. The plant tends to maintain an equilibrium between nitrogen and carbohydrate by varying the area of the leaf and changing the amount of assimilation. Beyond a certain range, however, this method of adjustment becomes insufficient. The efficiency of the leaf as a producer of carbohydrate may then be raised by increasing the supply of potassium or of phosphorus, whichever is present in the smaller quantity: the

[1] *J. Agric. Sci.*, 1936, **26**, 391.

equilibrium is thus maintained. Beyond a further point this method in turn ceases to suffice and then marked alteration in composition begins; nitrogen compounds pile up in the plant in excess of their usual amount (Fig. 6). As the proportion of nitrogen increases so the plant alters: the normal functioning of the plant organs seems to proceed only within a somewhat narrow range of values for the $\frac{\text{carbon}}{\text{nitrogen}}$ ratio:

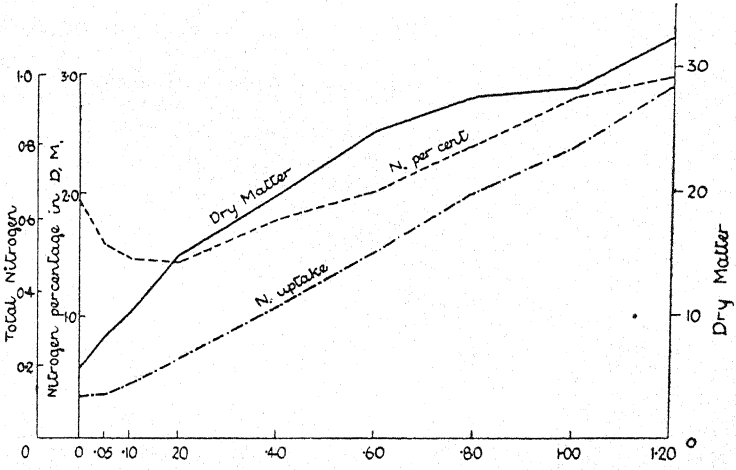


FIG. 6.—Nitrogen uptake and dry matter production and composition, Mustard (Rothamsted Pot Experiments).

flowering, fruiting, and other activities are suspended, or at least changed, if the value lies outside.[1] The harmful effects, described on page 66, appear when the proportion of nitrogen becomes unduly high.

This excess of nitrogen compounds reduces the proportion of all the constituents so far determined:[2] the percentages of carbohydrates, of the total ash constituents, of potassium and

[1] E. J. Kraus and H. R. Kraybill, *Oregon Agric. Expt. Sta. Bull.* No. 149, 1918, first drew attention to the importance of the C/N ratio. For a later discussion see M. A. H. Tincker, *Ann. Bot.*, 1928, **42**, 101.

[2] The calcium may be increased, however, where ammonium sulphate is used.

TABLE 14.—EFFECT OF NITROGEN SUPPLY ON PERCENTAGE COMPOSITION OF DRY MATTER.

(1) *Wheat, Rothamsted: Average 16 Years, 1848-1863.*

Wheat.	Yield, lb. per Acre.	Percentage Composition of Dry Matter.						
		N.	Ash.	P_2O_5.	K_2O.	CaO.	MgO.	SiO_2.
Straw.								
86 lb. N supplied per acre.[1] .	2663	0·67	5·32	0·16	0·87	0·32	0·09	3·45
No nitrogen .	1663	0·50	6·44	0·24	0·93	0·25	0·13	4·50
Grain.								
86 lb. N supplied per acre [1] .	1525	2·15	1·80	0·85	0·60	0·07	0·19	—
No nitrogen .	990	1·90	2·01	1·00	0·66	0·06	0·03	—

(2) *Cocksfoot (Dactylis glomerata), Aberystwyth.*[2]

	Percentage Composition of Dry Matter.				
	N.	Ash.	P_2O_5.	CaO.	SiO_2.
Leaf.					
34·5 lb. N[3] per acre .	3·21	12·57	0·84	0·77	4·05
No nitrogen . .	2·92	13·30	0·91	0·85	4·92
Stem.					
34·5 lb. N[3] per acre .	2·02	11·57	0·86	0·48	3·95
No nitrogen . .	1·65	12·05	0·98	0·57	3·68

phosphate in the dry matter all decrease. The reduction in carbohydrate is partly at any rate due to their interaction with the assimilated nitrogen to form complex nitrogen compounds, but it is not known whether this involves any important changes in the mineral constituents. The ratio of $K_2O : P_2O_5$ in sugar beet showed no consistent changes with increasing nitrogen supply in the Bernburg experiments.[4]

In barley grain, as the total percentage of nitrogen increases so the relative proportion of hordein increases, while that of

[1] As sulphate of ammonia.

[2] T. W. Fagan and R. E. Evans, *Welsh J. Agric.*, 1926, **2**, 113.

[3] As nitrate of soda (2 cwt. per acre).

[4] "Der Nährstoffbedarf der Zuckerrübe," W. Krüger, G. Wimmer, *et alii, Mitt. Anhalt. Vers.-Sta. Bernburg*, No. 60, 1927, 1-33.

the salt soluble nitrogen decreases: the proportion of glutelin, however, remains constant (Fig. 7). The proportions are the same whether the changes in total nitrogen result from soil or

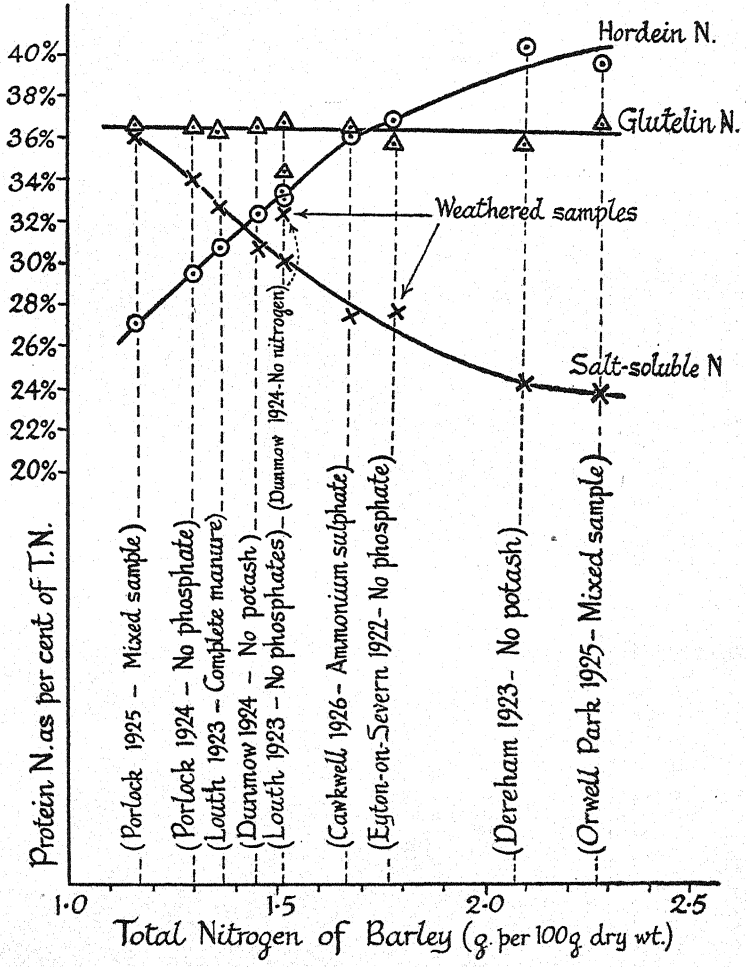


FIG. 7.—Relation between the total nitrogen content (T.N.) and the quantities of the various proteins present in barley grain (Plumage Archer), (L. R. Bishop).

climatic factors or additions of nitrogenous fertilisers: they appear to be varietal constants.[1]

[1] L. R. Bishop, *J. Inst. Brew.*, 1928, **34**, 101.

The increased nitrogen content of barley grain beyond a total percentage of about 1·4 is usually detrimental to malting

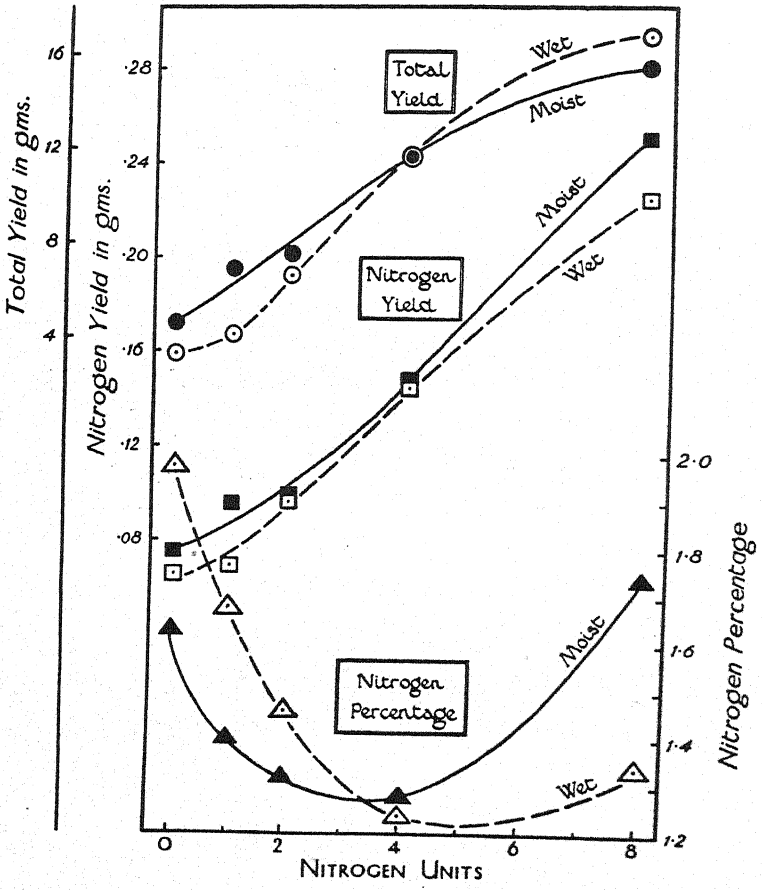


FIG. 8.—This shows the yield of barley grain, its uptake of nitrogen and its nitrogen percentage when grown under restricted and under fuller conditions of water supply ("moist" and "wet") respectively. As the nitrogen supply increases, so the uptake of nitrogen ("nitrogen yield") increases also, but the yield increases still more, so that the nitrogen percentage falls. Beyond a certain limit, however, the increase in yield no longer keeps pace with the increase in nitrogen uptake, so that the percentage of nitrogen in the grain now rises.

This limit is not fixed, but changes with the water supply and other conditions (Woburn Pot Culture Experiments, 1931).

quality, while the increased percentage in wheat is usually but by no means always beneficial to baking quality.[1]

The reduction in sugar content of the roots of sugar beet receiving nitrogenous fertiliser is of considerable practical importance. The yields of roots are increased by nitrogenous fertiliser, but in the Rothamsted experiments the sugar percentage was not infrequently lowered by as much as 0·6 per cent.

The effects are modified by variations in water supply, as shown in Fig. 8, giving results obtained in the Woburn pot experiments with barley. With low supplies of nitrogen the plants grown on the wetter soil yield less grain containing a higher percentage of nitrogen than those on the drier soil, while with larger supplies of nitrogen the position was reversed; the grain grown on the wetter soil was larger in quantity but contained a lower percentage of nitrogen than on the drier soil. Neidig and Snyder obtained somewhat similar results with wheat in the Idaho pot experiments. At the optimum moisture content with adequate nitrogen for growth but no excess for the ripening period the yield of grain was high and its nitrogen content low. When, however, the moisture supply was less the yields fell off but the nitrogen content was higher. If the moisture content and the nitrogen supply were both high the yield and the nitrogen content of the grain were also high.[2]

Phosphorus Nutrition of Plants.

Phosphates are by far the most efficient phosphorus nutrients known for plants. Ortho- and pyro-phosphates are equally effective for wheat and barley but metaphosphate is less readily assimilated, especially the *b*-modification, presumably on account of the larger size of the molecule which

[1] For Idaho data relating percentage of nitrogen in soil to percentage in wheat grain see R. E. Neidig and R. S. Snyder, *Idaho Agric. Expt. Sta. Res. Bull.* No. 5, 1926.

[2] R. E. Neidig and R. S. Snyder, *Soil Sci.*, 1924, **18**, 173.

renders its entry into the root difficult.[1] The effects are less striking than those of nitrogen compounds, and can be recognised only by comparing plants receiving sufficient phosphate with those receiving but little. Different plants vary also in their sensitiveness to phosphate starvation.

The most obvious effects are on the root system, the tillering of cereals, and the production of seed. So long ago as 1847 Lawes wrote: "Whether or not superphosphate of lime owes much of its effect to its chemical actions in the soil, it is certainly true that it causes a much enhanced development of the *underground* collective apparatus of the plant, especially of *lateral* and fibrous *root*, distributing a complete network to a considerable distance round the plant, and throwing innumerable mouths to the surface." Dressings of phosphate are particularly effective wherever greater root development is required than the soil conditions normally bring about. They are invaluable on clay soils, where roots do not naturally form well, but, on the other hand, they are less needed on sands, because great root growth normally takes place on these soils. They are used for all root crops like swedes, turnips, potatoes, and mangolds; in their absence swedes or turnip roots will not swell but remain permanently dwarfed like radishes. Fig. 9 shows one of Lawes and Gilbert's experiments. The introduction of superphosphate as a fertiliser revolutionised agriculture on some of the heavier soils by allowing better growth of these crops.

Cereals suffering from phosphate starvation are retarded in every stage of their life history, from the emergence of the second leaf to the time of ripening. They have a stunted root system, especially in their early days, and an even more stunted leaf and stem; when phosphates are given the shoot increases more than the root, *i.e.* the ratio root/shoot is diminished. Phosphate starvation also depresses tillering, causing a decrease in total number of tillers and in number of tillers bearing seed. Similar stunting of the roots, shoots and leaves is

[1] S. Glixelli and K. Boratynski, *Rocz. Nauk Roln.*, 1933, **30**, 342.

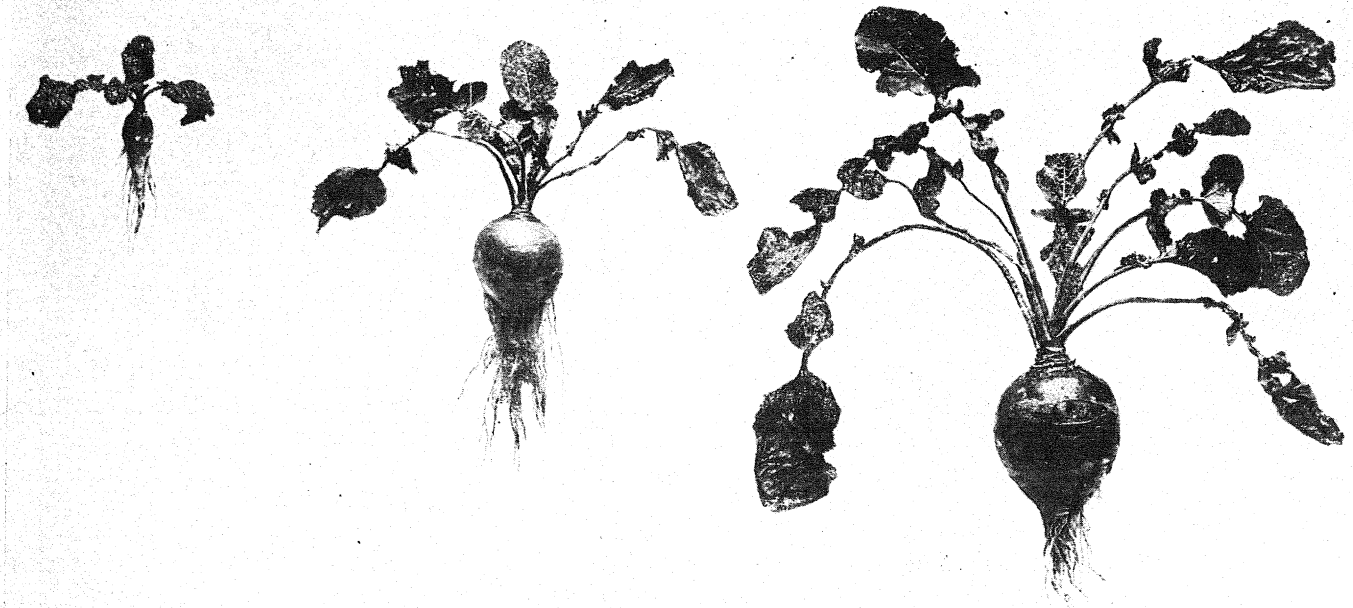


FIG. 9.—Swedes from Agdell field, Broadbalk : unmanured ; superphosphate and potassic fertilisers ; and complete fertiliser (Lawes and Gilbert).

seen in phosphate-starved fruit trees.[1] The roots consist mainly of coarse brown rootlets.

Phosphate-starved barley becomes reddish in the stem in water cultures and a sickly purple in the leaf in extreme cases in soil,[2] but only a dull greyish-green on the Hoos Field at Rothamsted. Phosphate-starved apple trees had bronze-purple coloured leaves, often with purple or brown spots, carried mainly at the tops of the shoots because the lateral buds are killed.[3]

On soils deficient in phosphate, though not on others, phosphatic fertilisers hasten the ripening processes, thus producing the same effect as a deficiency of water, but to a less extent. This ripening effect is well shown on the barley plots at Rothamsted; crops receiving phosphates are golden-yellow in colour while those on the phosphate-starved plots are still green. Scott Robertson has given some very interesting examples.[4]

Certain indirect effects also follow: the head of the barley emerges from its ensheathing leaves a few days in advance of those receiving insufficient phosphate, and therefore has a better chance of escaping attack by the larvæ of the gout fly (*Chlorops tæniopus* Meig.), which, hatching from their eggs

TABLE 15.—EFFECT OF VARYING PHOSPHATE SUPPLY ON THE GROWTH OF BARLEY IN SAND CULTURES. HELLRIEGEL (1898).

Weight of P_2O_5 supplied, mgms. per pot	0	14·2	28·4	56·8	85·2	113·6	142	213	284
Weight of dry matter in crop, grams per pot	1·856	8·254	12·613	19·505	19·549	20·195	18·667	17·785	31·306
Grain per cent. of dry matter	—	22·4	31·8	38·4	41·6	43·8	41·3	40·1	43·4
Weight of one grain, mgms.	—	27	29	38	34	41	38	30	34

[1] T. Wallace, *J. Pomol. Hort. Sci.*, 1925, 4, 117, and **5**, 1.

[2] *E.g.* at Offchurch in Warwickshire, C. T. Gimingham, *Agric. Education Assoc. Repts.*, 1922, p. 19.

[3] T. Wallace, *J. Pomol. Hort. Sci.*, 1925, 4, 117, and **5**, 1; 1930, 8, 23.

[4] *J. Min. Agric. Northern Ireland*, 1927, 1, 7.

TABLE 16.—RESULTS OF WITHHOLDING PHOSPHATES, POTASSIUM COMPOUNDS, AND NITROGEN COMPOUNDS FROM BARLEY. HOOS FIELD EXPERIMENTS, ROTHAMSTED.

Plot.		Yield of Grain, 1000 lb. per Acre.					
		5 years, 1852-56.	5 years, 1857-61.	10 years, 1862-71.	20 years, 1872-91.	20 years, 1892-1911.	20 years. 1913-32.
7	Dung . .	2·31	2·78	3·00	2·77	2·53	1·90
A 4	Complete manure (salts of NH_4, K and P)	2·47	2·71	2·67	2·29	2·14	1·76
A 3	No phosphates	2·27	1·71	1·99	1·53	1·24	0·93
A 2	No potassium .	2·42	2·70	2·76	2·15	1·72	1·58
O 4	No nitrogen .	1·86	1·57	1·39	0·95	0·84	0·96

Plot.		Yield of Straw, 1000 lb. per Acre.					
		5 years, 1852-56.	5 years, 1857-61.	10 years, 1862-71.	20 years, 1872-91.	20 years, 1892-1911.	20 years, 1913-32.
	Dung . .	2·82	3·15	3·35	3·32	3·44	2·54
A 4	Complete manure (salts of NH_4, K and P)	3·29	3·17	3·14	2·62	2·60	2·01
A 3	No phosphates	2·86	2·03	2·20	1·70	1·66	1·36
A 2	No potassium .	3·21	3·03	3·07	2·25	2·03	1·64
O 4	No nitrogen .	2·03	1·58	1·42	0·94	1·14	1·28

on the top of the topmost leaf, crawl downwards seeking the head for food.

But addition of phosphate leads to no increase in the proportion of grain borne by the plant. On the Rothamsted plots supplied with nitrogen and potassium compounds, but no phosphate, the grain formed 44·9 per cent. of the total produce during the first ten years of the experiment (1852-1861), and almost exactly the same proportion (44·7 per cent.) during the fifth ten years (1892-1901) when phosphate starvation was very pronounced; it fell a little to 41·3 per cent. in the sixth ten years (1902-1911), but rose to 46·1 per cent. in the period 1913-1921. Later (1923-1928) it fell to 32·9, but rose to 37·4 in the period 1929-1935. Even in sand cultures the effect is not very marked: Hellriegel (1898) grew barley with varying

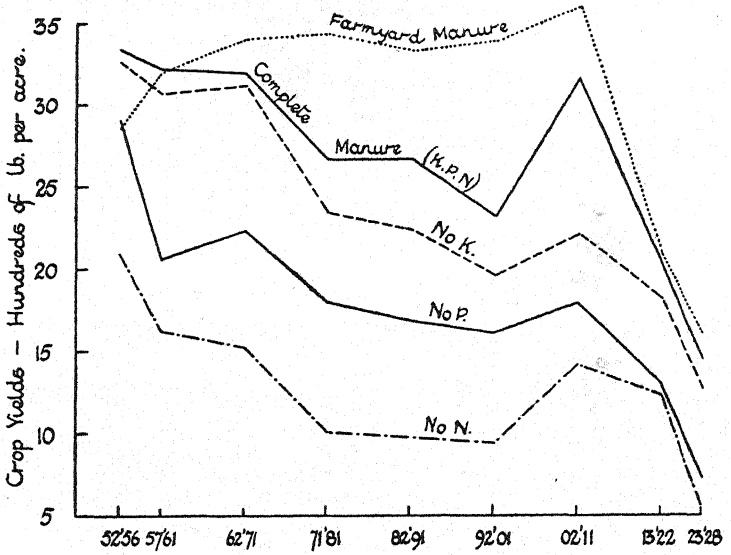


FIG. 10*a*.—Effect on yields of grain of withholding various nutrients from barley. Hoosfield, Rothamsted; Five-year Periods, 1852-1856 to 1923-1932.

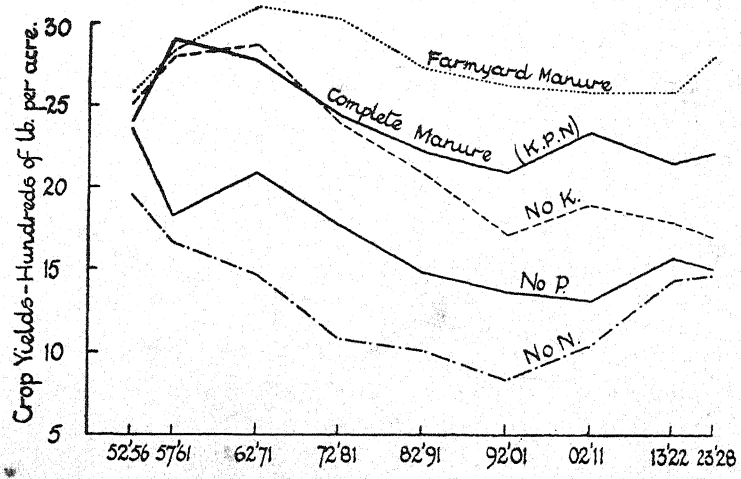


FIG. 10*b*.—Effect on yields of straw of withholding various nutrients from barley. Hoosfield, Rothamsted; Five-year Periods, 1852-1856 to 1923-1932.

supplies of phosphate with results given in Table 15. In absence of phosphate no grain was formed; when a little was added grain formation proceeded normally, and the resulting grain was nearly full weight per individual; as the phosphate supply increased the percentage of grain increased, but soon reached a maximum beyond which it would not go.

The Rothamsted results are plotted in Figs. 10*a* and 10*b*. The effect of phosphate starvation shows itself in depressing the yield of straw and of grain. Potash starvation takes longer to set in, not because potassium is less necessary but because the soil contains a larger quantity; it also affects the straw first. Nitrogen starvation sets in at once, rapidly bringing both grain and straw down to a low level.

With deficient phosphate supply plants apparently have some difficulty in getting their full supply of potassium (p. 83).

Action of Phosphate in the Plant.

Phosphorus is a constituent of the nucleus and is essential for cell division and for the development of meristem tissue. Further, it is needed for the normal transformations of the carbohydrates and for the efficiency of the chloroplast mechanism.

Gregory [1] shows that in sand cultures the first dose of phosphate increases both leaf area and efficiency: later doses, however, cause successively less and less improvement in efficiency but they continue to increase the rate of growth. There is thus a point of inflexion in the curve showing the relationship between amount of phosphate absorbed and amount of growth.

F. J. Richards [2] showed that progressive phosphate deficiency led to a progressive decrease in respiration. Several actions seem to be involved. The oxidation of sugar in the cell appears in the anaerobic phase to require the combination with phosphate to form a hexose phosphate which Harden

[1] *Proc. 5th Internat. Bot. Cong.*, Cambridge, 1930, p. 440.
[2] *Ann. Bot.*, 1937, **51**.

and Young [1] found necessary for the fermentation of sugar by yeast. In the aerobic phase the phosphate ion apparently stimulates the activity of the oxidising enzymes,[2] without, however, combining with sugar. Phosphate deficiency, like potassium deficiency, causes a progressive increase in the proportion of amino-acids, especially in the later leaves.

Excess of phosphate over the amount required by the plant has sometimes depressed crop yield.[3] This has usually occurred on light soils and has been attributed to the hastening of the maturation processes and consequent reduction of vegetative growth. Phosphate poisoning is occasionally reported, *e.g.* O. Lemmermann and W. U. Behrens [4] obtained satisfactory growth of oats in pot experiments when the proportions of the nutrients $P_2O_5 : K_2O : N = 1 : 1{\cdot}5 : 1$ but not when they were $3 : 1{\cdot}5 : 1$. With these higher doses of phosphate the leaves showed signs of physiological disease: red spots appeared which later shrivelled. When the proportion of potash was increased the extra phosphate produced no harmful effect. There is, however, no evidence of phosphate poisoning in normal conditions.

Plants seem unable to take up the whole of the phosphate from soil or sand cultures; they do not usually recover more than about 20-30 per cent. of the amount supplied.[5] From water cultures the recovery is higher and may amount to 40 or 50 per cent. The rate of absorption, however, varies with the acidity of the medium: for sugar cane in water cultures absorption is retarded as the solution becomes more nearly

[1] See A. Harden, *Alcoholic Fermentation* (Longmans, Green & Co.), 1933, and *Nature*, 1930, **125**, 277 and 313.

[2] C. J. Lyon, *J. Gen. Physiol.*, 1924, **6**, 299, and *Amer. J. Bot.*, 1927, **14**, 274. (Expts. with *Elodea* and wheat seedlings.)

[3] For instances see E. J. Russell, *J. Inst. Brew.*, 1923, **29**, 631 (barley); J. C. Wallace, *J. Min. Agric.*, 1926, **32**, 893; *Rothamsted Conf. Repts.* No. 16, 1934 (potatoes).

[4] *Ztschr. Pflanz. Düng.*, 1935, **37**, 300.

[5] *Rothamsted Annual Reports*, 1930, p. 47; 1933, p. 28.

neutral, which has been explained by supposing that the ion taken up is $^{-}H_2PO_4$, not $^{--}HPO_4$.[1]

Phosphate is most effective as a nutrient in the early part of the vegetation period. In W. E. Brenchley's[2] water cultures barley took up in the first six weeks of its life sufficient phosphate for full normal growth; where, however, phosphate was withheld for the first four weeks no ears were produced no matter how much was given later, and where it was withheld longer the habit of growth was completely altered. Strebeyko found that with increasing supply in the early stages of growth the uptake of nitrogen and of sulphur was also increased as also was the amount of protein synthesised. In the later part of the plant's life, however, the intake of nitrogen and of P_2O_5 per gram of increased dry matter was smaller at higher concentrations of P_2O_5 in the soil. The uptake of sulphur is closely connected with that of phosphate, and the ratio S/P is approximately constant and about = 1.[3]

Effect of Phosphate on the Chemical Composition of the Plant.

There is a general relationship between the amount of phosphate supplied to the plant and the amount taken up by the plant: this has been studied considerably by Neubauer, and indeed it forms the basis of his method of estimating the quantity of available phosphate in the soil. The relationship is of the logarithmic type, the curves resembling those of the Mitscherlich equation (p. 136). With low phosphate supply in the soil an addition of phosphate may markedly increase the amount of phosphate taken up by the plant; with higher phosphate supply the same addition of phosphate may cause but little additional uptake.

[1] T. H. van de Honert, *Bijeenkomst Vereen Proefstat. Personeel* (Passeroan, 1933). A. H. Lewis and K. J. Sinclair (*Emp. J. Expt. Agric.*, 1934, **2**, 154) and A. H. Lewis and D. Trevains (*ibid.*, 239) found that $(NH_4)_2HPO_4$ was sometimes toxic on sandy soils.

[2] *Ann. Bot.*, 1929, **43**, 89.

[3] P. Strebeyko, *Acta Soc. Bot. Poloniae*, 1934, **11**, 237.

TABLE 17.—EFFECT OF PHOSPHATE SUPPLY ON PHOSPHORUS CONTENT OF PLANTS: P_2O_5 PER CENT. IN DRY MATTER.

	Soils Deficient in Phosphate.		Soils not Deficient in Phosphate.	
	No Phosphate Given.	Superphosphate Given.	No Phosphate Given.	Superphosphate Given.
Barley.				
Straw: P_2O_5	0·44 [1]	0·89 [1]	—	—
Grain: P_2O_5	1·31	1·30	0·959 [2]	0·972 [2]
Pasture Grass.[3]				
P_2O_5	0·29	0·71	0·96	0·93
CaO	0·59	0·94	1·16	1·16
Cocksfoot.[4]				
Stem: P_2O_5			0·98	0·91
Leaf: P_2O_5			0·91	0·91
Stem: CaO			0·574	0·588
Leaf: CaO			0·847	0·868

Further illustrations are given in *Rothamsted Annual Report*, 1930, p 46.

The additional phosphate assimilated by the plant as the result of increased phosphate supply does not necessarily alter its composition. It may simply cause a corresponding increase in growth in which case the phosphorus content of the crop remains unchanged. Frequently, however, the increase in growth is less, and so the phosphorus content of the crop increases; this commonly happens on poor soils (Table 17); the phosphorus is apparently retained in the inorganic form. In better growth conditions, however, the added phosphate may be without effect on the crop either on yield or

[1] T. H. Mather, *Sci. Agric.*, 1929, **10**, 35. Alberta wood soil, Pot Experiments.

[2] Rothamsted Averages, 1923-24-25, Field Experiments.

[3] W. Godden, *J. Agric. Sci.*, 1926, **16**, 98. Similar results were obtained by G. Paturel in France, *J. Agric. Prat.*, 1911, **21**, 12-14; also A. E. V. Richardson in Victoria, *J. Dept. Agric. Victoria*, 1924, **22**, 193-207 and 257-270; in both cases the unmanured herbage contained only 0·25 or 0·26 per cent. P_2O_5, while that receiving phosphatic manuring contained distinctly more.

[4] T. W. Fagan and R. E. Evans, *Welsh J. Agric.*, 1926, **2**, 113. The authors state that the soil is deficient in phosphate, but the crop yields showed that no increase was given by superphosphate.

composition; it had but little action in the Rothamsted malting barley experiments or in the experiments with cereals made by A. W. Blair and J. G. Lipman at New Jersey.[1]

This relation between phosphate supply and phosphorus content of the crop is of great practical importance. Over large areas of the world soils are deficient in phosphate and the herbage they carry is therefore also deficient (Table 18);

TABLE 18.—P_2O_5 PER CENT. OF DRY MATTER IN GRASSLAND HERBAGE.

	Good Soils.		Poor Soils.
Romney Marsh [2] .	0·60	Transvaal Veld [4] .	0·10
Scotland [3] . .	0·74	Bechuanaland [5] .	0·04
		Victoria [6] . .	0·10

so much so that it may fail to supply grazing animals with all the phosphorus they need. The animals then suffer from a "deficiency disease" which may be very serious; a full investigation was made in South Africa by Arnold Theiler and his colleagues. The animals devour bones with great avidity, even putrefying bones, and so they become further liable to ptomaine poisoning.[7] The remedy is to treat the land with superphosphate; or if this is too costly to supply the animals with bone meal.[8] Similar diseases occur in Australia, where also the arable land benefits considerably from dressings of superphosphate. In the Romney Marsh the

[1] *New Jersey Agric. Expt. Station Report*, 1923, p. 213. For further results see A. W. Blair and A. L. Prince, *J. Agric. Res.*, 1932, **44**, 579.

[2] 1 per cent. CaO also present. A. D. Hall and E. J. Russell, *J. Agric. Sci.*, 1912, **4**, 339.

[3] 1 per cent. CaO also present. J. B. Orr, *Minerals in Pastures*; H. K. Lewis, 1929, p. 13.

[4] 0·32 per cent. CaO also present. H. Ingle, *J. Agric. Sci.*, 1908, **3**, 22.

[5] A. Theiler, 11th and 12th Vet. Repts., 1927, Union of S. Africa.

[6] H. Kincaid, *Proc. Roy. Soc. Vict.*, 1911, **23**, 363.

[7] A. Theiler, H. H. Green, and P. J. du Toit, *Journ. S. Africa Dept. Agric.*, 1924, **8**, 460.

[8] The idea of feeding salts to animals to supplement mineral deficiencies in the herbage has long been current among practical farmers. See J. McMillan, *Trans. Highland Agric. Soc.*, 1875, **7**, 91.

best fatting pastures are richer in phosphate than the poorer ones;[1] this is generally true in both England and France.

The relation between phosphate supply and amount of other elements in the plant has not been fully studied. In leaves of the crops so far examined (vines and tomatoes but not the mixed herbage of grass land) the percentage of K_2O in the dry matter rises when phosphate is supplied; for tomatoes the percentage of P_2O_5 falls when potash is supplied (Table 19).[2] Other plant constituents are almost certainly

TABLE 19.—THE EFFECT OF FERTILISERS ON COMPOSITION OF LEAVES.

	Per Cent. in Dry Matter.			
	N.	K_2O.	P_2O_5.	Total Ash.
(*a*) *Vine Leaves* (*Lagatu and Maume*).				
Complete fertiliser .	1·75	1·80	0·25	3·80
No phosphate . .	2·05	1·41	0·12	3·58
No potash . . .	1·40	0·95	0·24	2·59
No manure . . .	1·35	0·83	0·13	2·31
(*b*) *Tomato Leaves* (O. Owen). Average 4 years (1924-1927).				
Complete fertiliser .	4·01	7·03	·667	31·1
No phosphate . .	3·62	5·25	·593	32·3
No potash . . .	3·73	1·68	·890	27·3
No nitrogen . .	2·31	6·03	·586	31·7

affected by variations in the amount of phosphorus present. Protein synthesis is retarded in the meristems of phosphorus-starved plants so that there is a considerable accumulation of amides and amino-acids.[3] The ill-defined properties associated with "quality" seem to increase with the phosphorus content of the crop. Paturel has shown that the best wines contain most P_2O_5 (about 0·3 grm. per litre), the second and lower qualities containing successively less. Further, when the vintages for different years were arranged in order of their

[1] Hall and Russell, *J. Agric. Sci.*, 1912, **4**, 339.

[2] For vines: H. Lagatu and L. Maume, *Compt. Rend. Acad. Agric.*, 1927, **13**, 439. For tomatoes: O. Owen, *Cheshunt Repts.*, 1927, **13**, 103, and *J. Agric. Sci.*, 1929, **19**, 413.

[3] F. J. Richards and W. G. Templeman, *Ann. Bot.*, 1936, **50**, 367.

P_2O_5 content, a list was obtained almost identical with the order assigned by the wine merchants. Davis has emphasised the importance of phosphate supply for the indigo crop.[1]

Potassium Nutrition of Plants.

Potassium is associated with the efficiency of the leaf as an assimilator of carbon dioxide and a maker of plant substance. In barley plants deficiency of potassium shows itself in a reduced production of sugar or starch per unit area of leaf and in a reduced rate of movement of the sugar to the root, stem, etc. The phenomena differ according to the conditions and may indeed be reversed if the circumstances are sufficiently changed. Two widely different groups of effects have been observed according as the calcium-sodium ratio is high or low.

(1) *Low but Adequate Calcium Supply; Abundance of Sodium.*—F. G. Gregory and F. J. Richards and Shih made sand cultures with barley in which calcium supply, though low, was adequate for growth; sodium was given in considerable excess and phosphorus supplies were good. In these conditions a reduction in potassium supply did not affect meristematic activity, tillering, leaf production, nor leaf size, but the leaves were pale, yellowish-green, and showed no sign of reddening; their water content was high and they died early. The plants contained less carbohydrate but a high proportion of reducing sugars to sucrose.

These results agree with the Rothamsted field observations on wheat and mangolds (p. 87).

(2) *Abundant Calcium Supply; Little Sodium.*—G. Janssen and R. P. Bartholomew [2] found, on the other hand, that the meristematic activity was reduced as the potassium supply was restricted; the leaves became small and hard, dark green with a tendency to produce red pigment and they died early. The production of carbohydrates was diminished, but as less was used up for growth the quantity of sugars present in the plant was not diminished. As before, there was a higher

[1] Pusa Indigo Pub. No. 6, 1920.

[2] *J. Agric. Res.*, 1929, **38**, 447; and 1930, **40**, 243.

proportion of reducing sugars to sucrose. In these experiments calcium supply was excessive, no sodium was given, and only a moderate amount of phosphate.

G. T. Nightingale obtained results intermediate between these apparently contradictory sets of observations, the results in the early stages being like those of Janssen and Bartholemew, and in the later ones like those of Gregory and Richards.

There is some uncertainty as to how far translocation of carbohydrates in the plant is affected by potash starvation. Miss Hartt [1] obtained evidence that translocation was retarded in potash-starved sugar cane. Nightingale,[2] on the other hand, could find no such effect in the tomato nor could Watson in the potato.[3]

G. Rohde shows that potassium plays an important part in determining the translocation and the functioning of iron in plants, and thus explains its intimate relation with chlorophyll formation, assimilation, respiration and root development: all activities for which iron is essential.[4]

He further shows that the symptoms of potash starvation are identical with those brought about by cutting off the blue and other short wave light and growing plants only in red light.[5]

Potassium also plays an important part in the transformations of nitrogen compounds in the plant. In potash-starved plants the amino acids increase relative to the protein. It does not, of course, follow that this increase is due to any hampering of protein synthesis: Richards and Templeman suggest that it arises from the breakdown of protein in the prematurely dying leaves.[6]

[1] C. E. Hartt, *Plant Physiol.*, 1934, **9**, 453.

[2] G. T. Nightingale, L. G. Schermerhorn, W. R. Robbins, *N.J. Agric. Expt. Sta. Bull.* No. 499, 1930. [3] D. J. Watson, *Ann. Bot.*, 1936, **50**, 59.

[4] *Ztschr. Pflanzenkrank. u. Pflazenschutz*, 1935, **45**, 499; *Ztschr. Pflanz. Düng.*, 1935, **39**, 159; 1936, **44**, 1. He gives a detailed description of the symptoms of potash deficiencies in potatoes in *Ernährung der Pflanze*, 1935, **31**, 237. [5] *Ztschr. Pflanz. Düng.*, 1936, **44**, 247.

[6] In potash-starved plants the reserves of potassium are mobilised in the growing points, being drawn there from the older tissues (N. O. Penston, *Ann. Bot.*, 1931, **45**, 673).

Nitrate tends to accumulate in the potash-starved plants, indicating an interference with the activity of the reducase, which would otherwise reduce it to ammonia (p. 62). Nightingale showed that the sugar content of the leaf is maintained in the early stages of potash starvation, in spite of the reduced production of carbohydrates, and Eckerson [1] attributes this to the falling off in protein synthesis consequent on this stoppage of ammonia formation.

Włodek [2] has shown that potash starvation increases the activity of tyrosinase in potato tubers: a similar action possibly occurs in sugar beet.

The root development is also affected by potassium supplies. In potash-starved plants the ratio root/shoot falls.

Potassium supplies also affect the turgidity of the cell; this is further discussed on page 90.

Field Effects.

In natural conditions supplies of potassium may be adequate for low levels of nitrogen or phosphorus supply, but inadequate for higher levels. Signs of potash starvation may therefore set in when nitrogenous or phosphatic fertilisers are given without potassic fertilisers.

With small supplies of nitrogen the leaves of potash-starved plants are small but the proportion of carbohydrates to the nitrogen compounds in the plant, which are also small in amount, is not abnormal. The plant is stunted, and rather ashy-grey in colour, its leaves tending to die prematurely, dying first at the tips and then along the outer edges; otherwise it shows no striking abnormality until fruit or seeding time, when both fruit and seed tend to be small in quantity, in size and in weight. These effects are general, and are seen on all soils, but best on light sandy or chalky soils and on certain peaty soils; it is on these that potassic fertilisers are most likely to act on all crops.

[1] S. H. Eckerson, *Boyce Thompson Instn. Contr.*, 1931, **3**, 197.
[2] *Rocz. Nauk Roln.*, 1930, **23**, 367 (German summary).

The colour change due to lack of potassium differs from that due to lack of nitrogen: Włodek has shown that the proportions of chlorophyll α and chlorophyll β are differently affected.[1]

With large supplies of nitrogen, on the other hand, the uptake of nitrogen is considerable; the leaves are large but relatively inefficient owing to lack of potassium, and therefore produce less carbohydrates in proportion to their nitrogen compounds. There results, therefore, an abnormal excess of nitrogen compounds in the plant, which leads to various undesirable effects.

Potassium is thus the counterpart of nitrogen and phosphorus, which are associated with the size of the leaf; the two groups of nutrients are intimately linked in their action. It is well recognised in practice that neither potassic nor nitrogenous fertiliser gives its full effect without adequate supplies of the other.

The effect on leaf efficiency is shown in Table 20, giving

TABLE 20.—INFLUENCE OF POTASSIUM SALTS ON THE ACTION OF NITROGENOUS MANURES. ROTHAMSTED.

	Average Weights, Mangolds, 50 years, 1876-1928.[2]					
	Roots, 1000 lb. per Acre.			Leaves, 1000 lb. per Acre.		
Insufficient potassium (Series 5)	10·01	15·01	21·26	2·35	5·85	7·37
Sufficient potassium (Series 6) .	9·03	30·24	50·51	2·08	6·29	11.65
Nitrogen supplied in manure, lb. per acre	—	86[3]	184[4]	—	86[3]	184[4]
(Cross dressing) . . .	0	A	AC	0	A	AC

the weight of mangolds obtained on certain of the plots at Rothamsted, some being well supplied with potassic fertiliser and others not, but all receiving adequate phosphate. In

[1] *Bull. Acad. Polonaise*, 1920, B, p. 19; 1921, B, p. 143 (in French); *Rocz. Nauk Roln.*, 1930, **23**, 367.

[2] Excluding 1885 when nitrogenous fertilisers were not applied owing to poverty of crop, and 1908 and 1927 when the crop failed.

[3] From 400 lb. ammonium salts to 1915; 412 lb. sulphate of ammonia since.

[4] As for (2), and in addition 2000 lb. rape cake.

series A, where ample but not excessive nitrogen is given, the weight of leaves is the same whether potassic fertiliser be given or not. But in absence of potassium the leaves are only about half as effective, making only about half as much root as when it is given.

The liability to disease resulting from excess of nitrogen is diminished by supplying potassic nutrients.

On the Rothamsted plots receiving excess of nitrogen but no potash wheat may be attacked by rust and mangolds by *Uromyces betæ* and a black bacterial blotch, while the surrounding plots, equally liable to infection but receiving adequate amounts of potassic fertiliser, are less affected. At the Woburn Experiment Station potassic fertiliser reduced the attack of *Fusarium culmorum* on barley; the relative attacks were:—

No potassic fertiliser.	Potassium sulphate.
47	31

Neither superphosphate nor nitrogenous fertilisers had this effect. At the Cheshunt Experiment Station, potassic fertilisers reduce the liability of tomatoes to the "streak" disease and also to "blotchy ripening" [1] (Table 21).

TABLE 21.—YIELD AND CHARACTER OF TOMATO FRUIT FROM PLANTS RECEIVING DIFFERENT AMOUNTS OF NUTRIENTS.

Dose of Nutrient.	Varying Potassium.		Varying Nitrogen.		Varying Phosphate.	
	Tons [2] per Acre.	Per Cent. Blotchy Fruit.	Tons per Acre.	Per Cent. Blotchy Fruit.	Tons per Acre.	Per Cent. Blotchy Fruit.
0	45·00	18·07	40·56	3·75	44·60	2·22
1	45·19	6·22	48·72	0·78	44·53	1·37
2	46·73	4·39	51·00	0·16	44·60	0·18
3	50·99	3·57	53·88	0·27	47·92	0·44

[1] *Cheshunt Expt. Stn.*, 11th Report, 1925. The percentages of nutrients in the fertiliser were:—

Potash (K_2O)	0	$2\frac{1}{2}$	5	$7\frac{1}{2}$
Nitrogen	0	$1\frac{1}{4}$	$2\frac{1}{2}$	5
Phosphates (as tricalcic phosphate)	0	8	16	24

[2] 1 ton = 2240 lb.

The numbers of plants affected with " streak " disease out of a total of 120 in each plot were :—

	Complete Fertiliser.	No Potassic Fertiliser.
Var. Comet . . .	40	78
Var. Kondine Red . .	13	33

The appearance of the leaves receiving inadequate supplies of potassium relative to their nitrogen is very striking. They become dull in colour, die at the tips and along the edges: the appearance is as if they were scorched; grass, cereals, fruit, tomatoes all show these symptoms. Later in the season the leaf ages prematurely and becomes " bronzed " or " coppered." Small brown spots appear on the younger leaves coalescing later to form brown patches: this is shown by potatoes and young orange trees. Shoots of fruit trees suffer at the tips; these first lose their leaves and then die; the lateral buds are less affected, so that the tree growth may continue but it is stunted. The proportion of fruit buds may be unusually large.[1]

This effect of potassium in correcting the harmful action of excess of nitrogen is in part at any rate attributable to its effect in increasing the net production of sugar and starch in the leaf, thus restoring to more normal values the C/N ratio which has been disturbed by excessive supply of nitrogen. The detailed analysis is being made by F. G. Gregory and other of Professor V. H. Blackman's investigators working at Rothamsted.[2]

Potassic fertilisers also decrease the rate of respiration. Gregory and Richards thus summarise the effects of deficiencies of the various nutrients :—

[1] For studies of fruit trees see T. Wallace, *J. Pomol. Hort. Sci.*, 1928, **7**, 1. For tomatoes, W. F. Bewley and H. L. White, *Ann. Appl. Biol.*, 1926, **13**, 323. For potato foliage, W. O. James, *Ann. Bot.*, 1930, **44**, 173, and 1931, **45**, 425. For tobacco, W. W. Garner and others, *J. Agric. Res.*, 1923, **23**, 27. Orange trees, H. S. Reed and A. R. C. Haas, *Calif. Agric. Expt. Sta. Tech. Paper* 11, 1923.

[2] F. G. Gregory and F. J. Richards, *Ann. Bot.*, 1929, **43**, 119-161; E. J. Maskell, *ibid.*, 1927, **41**, 327; W. O. James, *ibid.*, 1930, **44**, 173.

	Deficiency of		
	Nitrogen.	Phosphate.	Potassium.
Respiration .	Reduction (almost linear)	Reduction (non-linear. Diminishing effect)	Marked increase
Assimilation .	Slight reduction	Reduction	Marked reduction followed by an increase

The effect of potassium in increasing the efficiency of the leaf may explain why potassic fertilisers act well in cold sunless seasons: this has been observed on potatoes at Rothamsted [1] and tomatoes at Cheshunt.[2]

Potassium salts increase the turgidity of the leaf and stem [3] and so facilitate the entry of water into the plant; at the same time they decrease the amount of water transpired per unit of dry matter formed. This water-sparing effect falls off as the supply of potassium increases. Arland indeed claims that the effect is finally reversed and further supplies of potassium increase the transpiration and cause an extravagant use of water, but this has not been confirmed.[4] Wallace attributes some of the beneficial effects of potassium salts on fruit trees to this improvement in water supply which they bring about.

It will be seen later that potassium and calcium stand in marked contrast in relation to root development and uptake of water by the plant.

This effect on turgidity partly accounts for the tendency of potash-starved grasses and cereals to droop or fall. At Rothamsted the grass receiving no potassic fertiliser does not

[1] *Rothamsted Report*, 1927-1928, p. 22.

[2] W. F. Bewley, *Ann. Appl. Biol.*, 1929, **16**, 281.

[3] T. Weevers, *Rec. Trav. Bot. Neerland*, 1911, **8**, 289.

[4] Field plot experiments of A. Arland, *Ernähr. Pflanze*, 1931, **27**, 445, following up older work by H. S. Reed, *Bot. Gaz.*, 1910, p. 81; J. Kisser, *Planta*, 1927, **3**, 562, and especially B. Hansteen-Cranner, *Jahrb. Wiss. Bot.*, 1914, **53**, 536-599.

stand up as well as adjoining grass well supplied with potassium. Wheat lacking potash tends to become lodged in wet weather. The effect is not wholly due to turgidity; there are anatomical differences, *e.g.* the lower nodes of potash-starved cereals become unable to carry the weight of leaf and stem.[1]

No explanation can yet be given for the marked effect of potassic salts on leguminous crops. In a mixed grass field clovers have less capacity for absorbing potassium from the soil solution than the grasses,[2] and in absence of potassic fertilisers they suffer from the competition: the potassium-starved grass plots at Rothamsted contain notably less clover than those fully manured, the actual depression fluctuating according to the season. It is not certain that these effects are connected with protein synthesis.[3] The effect of potassic fertilisers in increasing the winter hardness of lucerne has been attributed to the increase they cause in the amount of carbohydrate and protein stored in the root.[4]

The effect on ripening is well marked. Potassium-starved plants are not only stunted in growth like plants lacking nitrogen or phosphorus, but they may even fail to reach

TABLE 22.—EFFECT OF POTASSIUM SALTS ON THE DEVELOPMENT OF BARLEY. HELLRIEGEL (1898).

K_2O supplied, mgs.	0	23·5	47	70·5	94	188	282
Dry matter in crop, grams	2·271	5·414	9·024	11·636	15·302	20·946	29·766
Grain, per cent. of dry matter	—	4·8	21·5	27·2	30·1	38·5	42·7
Weight of one grain, mgms.	—	5	9·5	13	17	26	34

[1] F. R. Tubbs, *Ann. Bot.*, 1930, **44**, 147. For observations on *Dactylis* see O. N. Purvis, *J. Agric. Sci.*, 1919, **9**, 338.

[2] Lawes and Gilbert, *Phil. Trans.*, 1900, B, **192**, 156.

[3] T. Weevers, *Biochem. Ztschr.*, 1917, **78**, 354; J. Stoklasa, *ibid.*, 1917, **82**, 310-323.

[4] L. F. Graber, N. T. Nelson, W. A. Luekel, W. B. Albert, *Wis. Agric. Expt. Sta. Res. Bull.* No. 80, 1927.

maturity.[1] With small supplies of potassium, seed is formed but it is small: unlike phosphates and nitrates, potassium compounds have a very marked effect on the weight of the individual grains, as may be seen by comparing Table 22 with the corresponding Tables 15 (p. 75) and 28 (p. 134); indeed, to withhold potassium is the surest way of producing stunted grain. At Rothamsted the average weights in lb. per bushel of wheat for the ten years 1910-1919 were :—[2]

No Manure. Plot 3.	Farmyard Manure. Plot 2.	Complete Artificials. Plot 7.	Artificials without Nitrogen. Plot 5.	Artificials without Potassium. Plot 11.
61·5	62·3	62·2	61·8	60·7

During and after the ripening of cereals there may be a marked loss of potassium from the roots of the plant. Chlorine also is lost (p. 131).

Effect of Potassic Nutrients on the Composition of the Plant.

Potassium is freely absorbed by plants from the soil: indeed of all nutrients it is one of the most readily taken up.[3] It tends to accumulate in the leaf and stem rather than in the grain (see Table 42, p 233): potassic fertilisers thus raise the percentage of potassium and of total ash in the dry matter, but they lower the percentage of the other ash constituents, sodium, calcium, phosphorus: this is shown for vine and tomato leaves on page 83,[4] and for the mixed herbage of grass-

[1] H. Wiessmann, *Ztschr. Pflanz. Düng.*, 1923, A, **2**, 1.

[2] For other instances see A. Jacob, *ibid.*, 1929, B, **8**, 61.

[3] Recovery of 90 per cent. or more of added potassium salts is reported by H. Neubauer, W. Bonewitz, and A. Schottmüller, *ibid.*, 1928, A, **12**, 108; *Landw. Vers.-Sta.*, 1928, **107**, 131; F. Honcamp and H. Wiessmann, *Fortschr. Landw.*, 1928, **3**, 931.

[4] In the *J. Kent Farmers' Union*, 1929, **25**, 172-177, Wallace gives the following figures showing the effect of potassic manuring on the

land in Table 23. Many analyses of this latter type have been made because of the agricultural importance of grassland ; [1]

TABLE 23.—COMPOSITION OF THE HERBAGE OF THE GRASS PLOTS AT ROTHAMSTED. AVERAGE 18 YEARS, 1856–1873.

	Nitrogenous Fertilisers.		No Nitrogenous Fertilisers.	
	N.P. No K.	N.P.K.	P only. No K.	P.K.
Plot . .	4–2	9	4–1	7
Per cent. in dry matter.				
K_2O . .	0·98	2·58	1·32	2·77
Na_2O . .	0·59	0·28	0·56	0·12
CaO . .	0·91	0·60	1·17	0·96
P_2O_5 . .	0·72	0·58	0·65	0·64
Ash . .	6·18	7·24	7·23	8·02
N . .	1·95	1·55	1·58	1·74
Per cent. in ash.				
K_2O . .	15·80	35·59	18·26	34·60
Na_2O . .	9·52	3·87	7·68	1·53
CaO . .	14·70	8·27	16·22	11·92
P_2O_5 . .	11·58	7·96	8·93	7·92

percentage of K_2O and P_2O_5 in the leaves and stems of gooseberries, vars. Careless and Whinham :—

	Red Currants.				Gooseberries.			
	Potash Treated Plot.		Control Plot.		Potash Treated Plot.		Control Plot.	
	Leaves, per cent.	Stems, per cent.	Leaves, per cent.	Stems, per cent.	Leaves, per cent.	Stems, per cent.	Leaves, per cent.	Stems, per cent.
K_2O in ash .	13·08	10·95	6·42	7·82	23·03	27·24	4·45	6·69
P_2O_5 ,, .	4·46	8·05	5·57	8·43	3·50	10·82	7·76	16·51
In dry matter:—								
K_2O . .	2·04	·785	·750	·207	2·33	1·36	·477	·325
P_2O_5 . .	·695	·577	·758	·566	·354	·541	·832	·802

[1] For recent Dahlem results see W. Lesch, *Ztschr. Pflanz. Düng.*, 1934, B, **13**, 211.

the effect, however, is complicated by the circumstance that shortage of potassium reduces the proportion of leguminous plants and so affects the entire flora.

When the proportion of potassium in the plant falls too low the whole plant becomes enfeebled. T. Wallace gives the following results, showing the relation between potassium in the leaf and health of gooseberries :—

	On Clay Areas.		On Sand Areas.	
	Healthy.	Slightly Affected.	Partial Failure.	Total Failure.
Ash in dry matter .	12·55	9·25	8·58	8·90
K_2O in ash . . .	23·11	17·92	6·63	3·86

The effect of variations in potassium supply on the organic compounds in plants is not great in ordinary circumstances. Most of the work has been done on sugar beet : Schneidewind, summarising the results, shows that potassic fertilisers on the average have raised the sugar content about 0·3 per cent.,

TABLE 24.—EFFECT OF POTASSIC FERTILISERS ON COMPOSITION OF MANGOLDS : EXCESS NITROGEN SUPPLY. AVERAGE 1878-1883.[1]

	No Potassic Fertiliser, per Cent.	Potassic Fertiliser, per Cent.	No Potassic Fertiliser, lb. per Acre.	Potassic Fertiliser, lb. per Acre.
Plot	5A	6A	5A	6A
Dry matter in root .	13·76	13·73	2583	4347
,, ,, ,, leaf .	10·68	10·24	715	603
Nitrogen in dry matter : root . . .	1·49	1·16	38·6	50·2
Nitrogen in dry matter : leaf	2·86	2·86	20·5	17·3
Sugar in root (1877-80).	8·68	8·36	1696	2407

[1] See E. J. Russell, "Artificial Fertilisers," *Min. Agric. Bull.* No. 28, 1933, p. 142. For other studies of potassic fertilisers see *Arbeiten über Kalidüngung*, O. Eckstein, A. Jacob, and F. Alten (*Landw. Vers.-Sta. Berlin-Lichterfelde*, 1931).

but they had little effect on the purity of the juice. In the English experiments organised from Rothamsted the rise in sugar content was of the same order (+ 0·2 per cent.). Rothamsted analyses of potatoes show that while nitrogenous fertilisers clearly raise the percentage of nitrogen in the tuber potassic fertilisers only slightly lower it :—

Amount of K_2O applied, cwt. per acre	0	0·4	0·8
N per cent. in dry matter of tubers .	1·42	1·38	1·39

i.e. a reduction in the percentage of protein of 0·25 and a corresponding gain in the carbohydrate and ash. More pronounced reductions of nitrogen content and increase in carbohydrate content are obtained in the extreme cases when excessive quantities of nitrogen have been given : for the Barnfield mangolds the results are given in Table 24.

Other Alkali Metals.

Sodium does not appear to be essential even to salt marsh plants, although *Salicornia* grew better in presence of salt than in its absence.[1] Some cultivated crops, mangolds, sugar beet [2] and, according to Heinrich,[3] peas, respond to dressings of salt, and the effect apparently is different from that of potassium salts. In addition sodium has the more general action that for a number of plants it can partially, but not completely, replace potassium as a plant nutrient ; it thus delays the setting in of potash starvation, but will not keep it off altogether.[4] Hellriegel (1898) found that sodium salts always gave increases in crop even when potassium salts were present in quantity (Table 25). Field experiments show that this is commonly true for sugar beet, barley

[1] A. C. Halket, *Ann. Bot.*, 1915, **29**, 143-154.

[2] *Rothamsted Report*, 1930, p. 34.

[3] *Ztschr. Pflanz. Düng.*, 1928, A, **10**, 299.

[4] See also p. 234. For a discussion of the protective action of sodium see W. J. Osterhout, *Univ. Calif. Publ. Bot.*, 1908, **3**, 331, and *Bot. Gaz.*, 1909, **48**, 98.

and summer wheat.[1] The sodium and magnesium salts present in some potassic fertilisers are of special importance in poor acid sandy soils in assisting the physiological adjustment of the soil solution to the barley plant: the effect is the same as a reduction of concentration of the hydrogen ions.[2]

TABLE 25.—EFFECT OF SODIUM SALTS WITH SMALL AND WITH LARGE AMOUNTS OF POTASSIUM SALTS ON THE GROWTH OF BARLEY. HELLRIEGEL (1898).

K_2O supplied, mgs. . .	0	94	188	282	376
Dry matter produced when sodium salts added . .	4·925	23·019	32·278	36·535	38·270
Dry matter produced when no sodium salts added . .	2·658	15·638	29·724	34·897	36·281
Difference due to sodium salts	2·267	7·381	2·554	1·638	1·989

It is well ascertained in farming practice that sodium salts can be used with great effect as manures wherever there is any deficiency of potash in the soil.[3] In these conditions sodium nitrate is more effective than calcium nitrate and particularly more than ammonium sulphate.[4]

J. A. Voelcker [5] has made the interesting observation that sodium hydroxide and sodium carbonate, unlike most other salts, cause an increase in the percentage of nitrogen in the wheat grain, besides increasing the yield of crop. The sulphate and the chloride increased the crop, but beyond a

[1] For a discussion of the factors involved see F. Terlikowski and A. Byczkowski, *Rocz. Nauk Roln.*, 1934, **31**, 89; also M. Gorski and K. Iwaszkiewiczowna, *ibid.*, 324.

[2] A. Byczkowski, *ibid.*, 1936, **37**, 131.

[3] See *Rhode Island Agric. Expt. Sta. Repts.*, 1905 to 1908, **19**, 186; **20**, 299; **21**, 243; Krüger, *Ztschr. Ver. Deut. Zuckerindust.*, 1914, 694. 702; B. Schulze, *Beitrag zur Frage der Düngung mit Natronsalzen (Landw. Vers.-Sta.*, 1913, **79**, 431, and 1915, **86**, 323-330); E. J. Russell, *J. Bd. Agric.*, 1915, **22**, 393-406.

[4] M. Kwinichidze, *Rocz. Nauk Roln.*, 1936, **37**, 222.

[5] *J. Roy. Agric. Soc.*, 1916, **77**, 262.

relatively low concentration limit further increases in amount of sodium chloride proved toxic.

Lithium salts, on the other hand, have a toxic action on plants. Gaunersdorfer's older experiments [1] have been confirmed by J. A. Voelcker (1912), who found that amounts of the chloride, sulphate, or nitrate corresponding to ·003 per cent. of the metal were distinctly injurious to wheat; smaller amounts, however, appeared to cause an increased growth. A mottled leaf disease can be induced in citrus plants by lithium salts.[2]

R. H. Biffen shows that a small quantity of lithium salts enables wheat to withstand rust.

Cæsium salts are less harmful than lithium salts (Voelcker).

Calcium Salts.

The first important work on the effects of calcium deficiency was done by Von Raumer and Kellermann: recent investigations have been made by G. T. Nightingale and his colleagues at the New Jersey Experiment Station.[3]

Deficiency of calcium in the nutrient supply usually leads to the following effects :—

1. Stunting and discolouring of the root. Maquenne and Demoussy [4] showed that root development of peas germinating in distilled water ceases after the third or fourth day, but is vigorously resumed on addition of even a trace of calcium sulphate: 0·01 mgm. per seed, representing an addition of calcium equal to 1/40,000 the weight of the dry seed, caused formation of root hairs and a 40 per cent. increase in root length. Reed and Haas [5] observed similar root effects

[1] *Landw. Vers.-Sta.*, 1887, **34**, 171-206.

[2] A. R. C. Haas, *Bot. Gaz.*, 1929, **87**, 630.

[3] G. T. Nightingale, R. M. Addoms, W. R. Robbins, and L. G. Schermerhorn, *Plant Physiol.*, 1931, **6**, 605. Tomato plants were used.

[4] *C.R.*, 1917, **164**, 979, and **165**, 45.

[5] H. S. Reed and A. R. C. Haas, *Calif. Agric. Expt. Sta. Tech. Papers* 4 and 11, 1923, and *Amer. J. Bot.*, 1924, **11**, 15. For the effect of calcium on the striking of cuttings see R. Cerighelli, *Bull. Soc. Bot. France*, 1926, **73**, 628.

with young orange trees, as did W. Newton [1] with potatoes, and J. M. Ginsburg with soy beans.[2]

In Nightingale's experiments the roots of tomato plants suffering from calcium deficiency were short and had numerous stubby branches: they were brown at the tips but well provided with root hairs.

2. Brown spotting and subsequent death of leaves, the new ones often being mottled or chlorotic: observed both by von Raumer and Kellermann [3] in the first serious studies of the effect of calcium, and by Reed and Haas.

3. According to Priestley: mobility of the fats in the plant so that they diffuse to the surface as shown in the thick cuticle and heavy suberin layers of the endodermis in plants growing in peat.[4]

Nightingale found a marked increase in the carbohydrates of calcium-deficient tomato plants, in consequence of which the late formed xylem had thicker walls than normally. While nitrate absorption by the roots was reduced the relative proportions of amino acids and protein in the plant were not much affected: this is in marked contrast with deficiencies of potassium, phosphorus, and sulphur. The quantity of nitrate, however, was lower than usual and the activity of the reducase was diminished.

In the calcium-deficient plants the percentage of calcium, magnesium, and phosphorus in the dry matter was reduced but that of potassium was decidedly high. This may explain why some of the effects of calcium deficiency are the reverse of those of potassium deficiency.

These effects on composition seem to be fairly general. Wallace shows that for fruit trees the chlorosis due to calcium deficiency may resemble in appearance that due to potassium

[1] W. Newton, *J. Amer. Soc. Agron.*, 1923, **15**, 392.

[2] *Soil Sci.*, 1925, **20**, 1-13. The effect on nodule formation is discussed by W. A. Albrecht and F. C. Davis, *ibid.*, 1929, **28**, 261.

[3] *Landw. Vers.-Sta.*, 1880, **25**, 25; 1883, **29**, 253.

[4] J. H. Priestley and M. Hinchcliff, *The Naturalist*, 1922, pp. 263-268; also J. H. Priestley, *New Phytol.*, 1924, **23**, 1-19.

deficiency (*e.g.* plum trees),[1] but a clear distinction is revealed on analysis of the leaves: calcium deficiency is associated with low dry matter, high ash, high potash, low calcium, while potassium deficiency is associated with high dry matter, low ash, low potash, high calcium.

Leguminous plants are usually rich in calcium, and it has been supposed that calcium plays, therefore, an important part in protein synthesis. But the result might equally be attributed to the large quantity of CO_2 evolved from the plant roots.

There is some evidence that calcium assists in neutralising organic acids in the plant. The mottled leaves of citrus trees starved of calcium are considerably more acid, but contain distinctly less calcium, than normal leaves.[2]

In general the addition of calcium greatly helps plants suffering through abnormal nutrition. In the laboratory the harmful effects of pure water or of single salts are more readily mitigated by calcium salts than by any others.[3] Gypsum is used on alkali soils to counteract the harm done through excess of sodium; and lime is added when an excess of magnesium is causing injury.

Calcium occurs in the plant in several combinations. Part is as calcium oxalate which forms crystals in the leaves, and part as calcium pectate which cements the cell walls together; some of it, however, appears to be in combination with the protein (Nightingale). Like the potassium, much of it remains in the leaf during the maturation processes.

Barium, Strontium, and Magnesium Compounds.

Barium and *strontium* cannot replace calcium in the nutrition of plants. McHargue[4] has shown that the carbonates are toxic, though in the presence of calcium carbonate

[1] *J. Pomol. Hort. Sci.*, 1928-1929, **7**, 172. For gooseberry bushes and apple trees the symptoms of the two deficiencies are not alike, calcium deficiency causing chlorosis, while potassium deficiency causes scorch.

[2] W. P. Kelley and A. B. Cummins, *J. Agric. Res.*, 1920, **20**, 161.

[3] R. H. True, *J. Amer. Soc. Agron.*, 1921, **13**, 91-107.

[4] *J. Agric. Res.*, 1919, **16**, 183.

they cause an increase in plant growth, strontium being more effective than barium. In Voelcker's experiments (1915) the addition to the soil of even 0·1 per cent. of strontium sulphate, hydrate, or carbonate was without effect, but the chloride was distinctly toxic.

Magnesium, like phosphorus, finally moves to the seed, and is thus in contrast with calcium and potassium, which mostly remain behind in the leaf of the straw.[1] Willstätter has shown (1908) chlorophyll to be a magnesium compound, an observation that accounts for the unhealthy condition of the chlorophyll bodies, and the final etiolation of magnesium-starved plants. The effect is well seen in water or sand cultures, and has been studied in detail for orange trees where chlorosis, due to magnesium starvation, spread from a narrow strip along the midrib;[2] for soy bean[3] where the leaves became spotted brown and fell off; and for fruit trees at Long Ashton. The leaves of apple trees developed characteristic brown patches in their centres, while more brilliant colours, as bright red, purple or yellow, were produced in the leaves of currants, gooseberries, and raspberries; sometimes colour developed along the leaf margins also, giving a three-zoned appearance. Death of the leaves and defoliation were invariably premature.[4]

Occasionally magnesium starvation occurs in nature. Wallace suggests that apples and raspberries may need magnesium salts where farmyard manure is not given, otherwise the magnesium deficiency causes serious premature defoliation preceded by characteristic colorations which serve to identify the trouble. In contradistinction to calcium, magnesium starvation does not affect the roots till comparatively late. Tobacco sometimes suffers in this way; a chlorosis known as

[1] Kelley and Cummins, however, show that potassium does not remain in the leaf of the citrus tree though magnesium does (*J. Agric. Res.*, 1920, **20**, 161).

[2] H. S. Reed and A. R. C. Haas, *Bot. Gaz.*, 1924, **77**, 290-299.

[3] J. M. Ginsburg, *Soil Sci.*, 1925, **20**, 1-13.

[4] T. Wallace, *J. Pomol. Hort. Sci.*, 1925, **4**, 117, and **5**, 1.

"Sand Drown" comes on in South Carolina, but it can be cured by supplying magnesium salts. This particular disease is aggravated by the presence of sulphates.[1] Potatoes sometimes respond to magnesium fertilisers, but the conditions are not clearly defined ;[2] Marholdt considers dung is essential to produce the effect.[3]

Further, magnesium seems to be necessary for the formation of oil, the globules being absent from algæ growing in solutions free from magnesium salts ; oil seeds are richer in magnesium than starch seeds.

An excess of magnesium salts produces harmful effects which, however, are lessened by addition of calcium salts ; Loew,[4] indeed, considered that plants require a definite $\frac{CaO}{MgO}$ ratio in their food, but neither Gössel[5] nor Lemmermann[6] could confirm this.

In J. A. Voelcker's experiments[7] magnesium oxide, carbonate, and chloride had, like sodium hydroxide, the unusual effect of causing an increase in the nitrogen content of the wheat grain. The sulphate did not act in this way, although in suitable small amounts it caused increases in yield of grain and of straw. The chloride proved toxic at higher concentrations.

Stimulative and Prophylactic Elements.[8]

Up to the present the elements known to have stimulative and prophylactic effects are boron, copper, iron, manganese,

[1] W. W. Garner, J. E. McMurtrey, C. W. Bacon, and E. G. Moss, *J. Agric. Res.*, 1923, **23**, 27-40.

[2] *Rothamsted Expt. Sta. Ann. Rept.*, 1921-1922, p. 19 ; M. Popp and J. Contzen, *Landw. Jahrb.*, 1923, **58**, 313 ; E. A. Mitscherlich and H. Wagner, *ibid.*, p. 645.

[3] *Landw. Vers.-Sta.*, 1923, **100**, 315.

[4] *U.S.D.A. Div. of Veg. Phys.*, Bull. No. 18, 1899.

[5] *Bied. Zbl.*, 1904, **33**, 226. [6] *Landw. Jahrb.*, 1911, **40**, 173 and 255.

[7] *J. Roy. Agric. Soc.*, 1915, **76**, 354 ; 1916, **77**, 260.

[8] For full summaries of the present position in regard to these elements, see "Soil Deficiencies and Plant Diseases," *Imp. Bur. Soil Sci. Tech. Comm.* 31, 1934, and W. E. Brenchley, *Bot. Rev.*, 1936, **2**, 173.

zinc, and possibly cobalt and aluminium. Of these, boron, iron, and manganese are essential in all conditions; absence of any of them shows itself in the cessation of some vital process, and usually the appearance of definite disease symptoms. Copper and zinc are apparently prophylactic in their effects; in some soil conditions plants seem specially liable to certain physiological diseases curable by these elements. W. A. Roach has devised an ingenious method of ascertaining which particular element is lacking. He cuts off the tips of a number of leaves on the diseased tree, and then without breaking them off, bends the leaves into tubes, each of which contains a dilute solution of the substance to be tested, *e.g.* a salt of iron, copper, manganese, etc. The substance that has really been lacking, and the absence of which has caused the trouble, causes the leaf to become a healthy green colour: the other substances do not.[1]

Although necessary in small amounts these elements are all toxic in larger concentrations. Their use in horticulture and in agriculture has therefore to be very carefully controlled.

Iron.

In absence of iron plants become chlorotic. It is not a constituent of chlorophyll and the chlorotic leaves under certain conditions actually contain more iron than healthy leaves, though as it is precipitated as phosphate in the vascular bundles it apparently cannot pass into the mesophyll.[2] Without iron, however, the chlorophyll does not develop in ordinary water or sand culture conditions. The action is not known with certainty, nor is it known whether any other substance would have the same effect, though a few observations which deserve further investigation seem to show that iron is not unique in its action.

The experiments of Oddo and Polacci suggested that the

[1] *East Malling Research Station Report*, 1935, p. 134.
[2] C. Olsen, *C.R. Lab. Carlsberg*, 1935, **21**, 15.

magnesium salt of pyrrole carboxylic acid would serve instead ; [1] while Boresch claims that chromates and manganates added together to culture solutions free from iron cause rebuilding of the chlorophyll exactly as if iron had been supplied.[2]

Usually soils contain sufficient iron for plant requirements so that additions are needed only for the water or sand cultures of plant physiologists ; occasionally, however, soils carry a chlorotic vegetation which becomes normal after iron salts have been added. Deficiency of iron in the herbage in the Rotorua region of New Zealand, was shown by B. C. Aston [3] to cause a disease known as bush sickness affecting cattle, and to a less extent sheep. "Pine," a disease of sheep and young cattle in certain northern regions of Great Britain, may be due to the same cause.[4] The harmful effect of calcium carbonate on certain plants has been attributed to a precipitation of iron in the soil (see p. 237).

Only little iron is found in plants, and that is not all in an active form ; part is deposited or precipitated as Fe_2O_3 in the leaf or the tissues. The active form was supposed by Maquenne [5] to be organic, akin to Bunge's hæmatogen ; Oserkowsky,[6] on the other hand, considers that it is the ionised iron. In any case the iron is continuously translocated towards the organs of active life and reproduction.

Manganese.

Numerous old field experiments suggested that manganese sulphate sometimes increased crop growth, but there were also

[1] *Gaz. Chim. Ital.*, 1920, **50**, 54.

[2] K. Boresch, *Ber. Deut. Bot. Ges.*, 1924, **42**, 284-290.

[3] *Trans. N.Z. Inst.*, 1911, **44**, 288, and later papers ; *J. N.Z. Dept. Agric.*, 1928, **36**, 316, and earlier papers. T. Rigg and H. O. Askew (*Emp. J. Expt. Agric.*, 1936, **4**, 1) show, however, that iron deficiency is not the only factor. An acid extract of healthy soil cured the disease, but the efficacy of the extracts was not governed by their iron content.

[4] J. Russell Greig, *et alii*, *Vet. J.*, 1933, **89**, 99.

[5] L. Maquenne and R. Cerighelli, *C.R.*, 1921, **173**, 273. They estimated the total iron as 20 to 100 parts Fe per million of dry matter.

[6] J. Oserkowsky, *Plant Physiol.*, 1933, **8**, 449.

many negative results.[1] The first critical scientific work was done by Bertrand who showed that manganese is invariably present in plants, and he and others have shown that it is not merely a stimulant, as had been supposed, but is essential, though only in small quantities, for the normal development of all plants.[2]

From his experiments on the oxidation of lac by laccase,[3] Bertrand concluded that manganese is needed for the functioning of the oxidases. Little beyond this is known as to the part it plays in the physiology of the plant. Deficiency of manganese leads primarily to chlorosis of the leaves, but in its absence growth ceases and the growing points die. G. Rohde points out that the action of manganese in the plant is linked with that of nitrogen, in contradistinction to iron, which is linked with potassium.

The phenomena are well seen on the well-known acid plots of the Rhode Island Experiment Station. The acidity had been intensified by the use of sulphate of ammonia as fertiliser: it was remedied by the addition of lime. But this frequently made the leaves of oats, spinach, lettuce, beets, beans, and maize become chlorotic. Soluble iron salts proved to be no remedy, but a small dressing (1 or 2 lb. per acre) of manganese sulphate or chloride cured the trouble.[4] The chlorosis is not as pronounced as that induced by iron deficiency.[5]

Diseases curable by small dressings of soluble manganese

[1] *Bull. Coll. Agric.*, Tokyo, 1906 *et seq.*; *Studi e Ricerche di Chimica Agraria*, Pisa, 1906-1908; B. Schulze, *Landw. Vers.-Sta.*, 1915, **87**, 1-24; H. Vageler, *ibid.*, 1916, **88**, 159-242; J. A. Voelcker at the Woburn Experimental Station, *J. Roy. Agric. Soc.*, 1903, **64**, 348-364; E. P. Deatrick, *Cornell Agric. Expt. Sta. Mem.*, 1919, **19**, 371.

[2] G. Bertrand and M. Rosenblatt, *C.R.*, 1921, **173**, 333, show that supposed exceptions of Maumené (*ibid.*, 1884, **98**, 1416) all contain manganese. J. S. McHargue, *J. Agric. Res.*, 1923, **24**, 781; 1925, **30**, 193; G. Samuel and C. S. Piper, *Ann. Appl. Biol.*, 1929, **16**, 493.

[3] G. Bertrand, *C.R.*, 1897, **124**, 1032 and 1355.

[4] B. E. Gilbert, F. T. McLean, and L. J. Hardin, *Soil Sci.*, 1926, **22**, 437; B. E. Gilbert and F. T. McLean, *ibid.*, 1928, **26**, 27.

[5] G. Samuel: see also C. Olsen, *C.R. Lab. Carlsberg*, 1934, **20**, No. 2.

salts have been found in several countries and on a number of different crops. The first recognised was the "grey speck" disease of oats [1] (Dürrfleckenkrankheit), which occurs especially on fen soils in Northern Europe, but is known also in America and Australia: it is remedied by dressings of some 45 lb. manganese sulphate per acre. Tomatoes and other crops are affected on the Everglade soils in Florida. Gerretsen [2] has shown, however, that this particular disease is complicated by bacterial action.

The soils on which these diseases occur are not always markedly deficient in manganese, and treatments such as sterilisation by heat, acidification by sulphur or acid, or water-logging, may render sufficient available for normal growth.[3] The application of lime, on the other hand, accentuates the deficiency. The availability of the manganese in soil is discussed on page 243.

Amounts of manganese in excess of plant requirements are toxic.[4] On the black soils of Hawaii containing appreciable quantities of manganese dioxide, pineapples suffer from "yellows," a disease in which there is pronounced chlorosis of the leaves, and root injury. This may be due to a direct toxic effect of manganese, combined with immobility of iron in the plant.[5]

Boron.

K. Warington [6] showed that broad beans attained full development only when a trace of boron was given: no other

[1] J. Hudig, *Rept. Int. Conf. Phytopath. Econ. Entom. Wageningen.*, 1923, p. 136; E. Hiltner, *Landw. Jahrb.*, 1924, **60**, 689; G. Samuel and C. S. Piper, *J. Agric. S. Aust.*, 1928, **31**, 696 and 789; R. C. Scott, *ibid.*, 1932, **35**, 771. For a summary see *Imp. Bur. Soil Sci. Tech. Comm.* No. 31, 1934.

[2] *Trans. 3rd Internat. Cong. Soil Sci.*, Oxford, 1935, **1**, 189.

[3] C. S. Piper, *J. Agric. Sci.*, 1931, **21**, 762. For other Australian data and discussion see G. W. Leeper, *Proc. Roy. Soc. Vict.*, 1935, **47**, 225.

[4] W. E. Brenchley, *Inorganic Plant Poisons and Stimulants*, 1914.

[5] W. T. McGeorge, *Soil Sci.*, 1923, **16**, 269.

[6] *Ann. Bot.*, 1923, **37**, 629.

element could replace it (Fig. 11). The best results were obtained with quantities of the order of one part of H_3BO_3 per million of the culture solution: amounts greater than 1 in 5000 were harmful. Boron appears to be connected in some way with the calcium nutrition of the plant.[1] Its most striking effect, however, is on the course of nodule development (p. 397). After the bacteria have entered the roots and begun to multiply, the normal event is for the main vascular system in the root to throw off a branch circulatory system surrounding the tissues containing the bacteria, supplying them with carbohydrates and other plant products, and removing the nitrogenous compounds made by the bacteria. W. E. Brenchley and H. G. Thornton[2] show that this branch system rarely forms in absence of boron: the bacteria remain without energy supplies from the plant, and in consequence become parasitic on the protoplasm of the host cells.

Sugar beet in various conditions, but especially on slightly alkaline or excessively limed soils, is liable to a "heart rot" disease which is curable by small dressings of borax (about 20 lb. per acre); the main growing point ceases to grow, as also do the youngest leaves; these become blackish-brown and brittle and die; the older leaves are later affected. This was first investigated by Brandenburg[3] in Holland; instances are now recorded from Ireland and Scotland. The harmful effect of excess of lime on sugar beet has been attributed to rendering the boron unavailable; the effect is said to be overcome by dressings of borax.[4]

"Brown heart" in swedes, a disease recorded in Canada, the South Island of New Zealand, and various parts of the British Islands;[5] "internal cork" of apples in

[1] K. Warington, *Ann. Bot.*, 1934, **48**, 743.

[2] *Proc. Roy. Soc.*, 1925, B, **98**, 373.

[3] E. Brandenburg, *Phytopath. Ztschr.*, 1931, **3**, 499; *Angew. Bot.*, 1932, **14**, 194. See also Saorstat Éireann, *J. Dept. Agric.*, 1935, **33**, 207; F. Hanley and J. C. Mann, *J. Min. Agric.*, 1936, **43**, 15.

[4] E. V. Bobko and M. A. Belvoussov, *Ann. Agron.*, 1933, **3**, 493. See also K. Scharrer and W. Schropp, *Phytopath. Ztschr.*, 1934, **7**, 245.

[5] T. Whitehead, *Welsh J. Agric.*, 1935, **11**, 235.

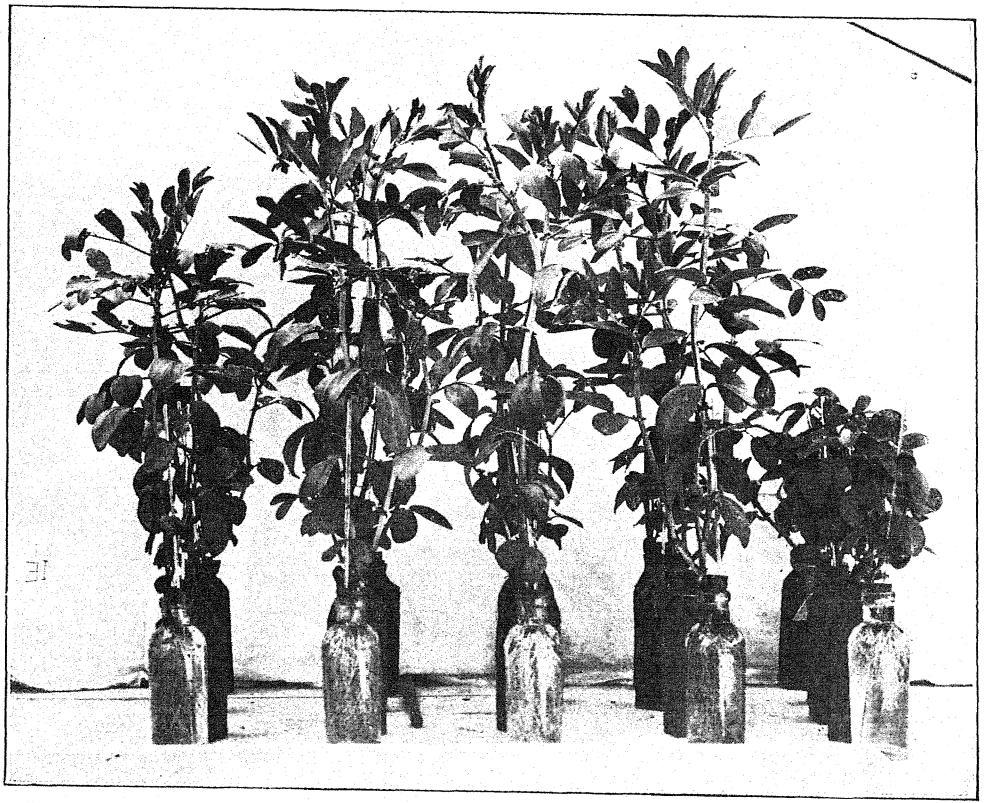
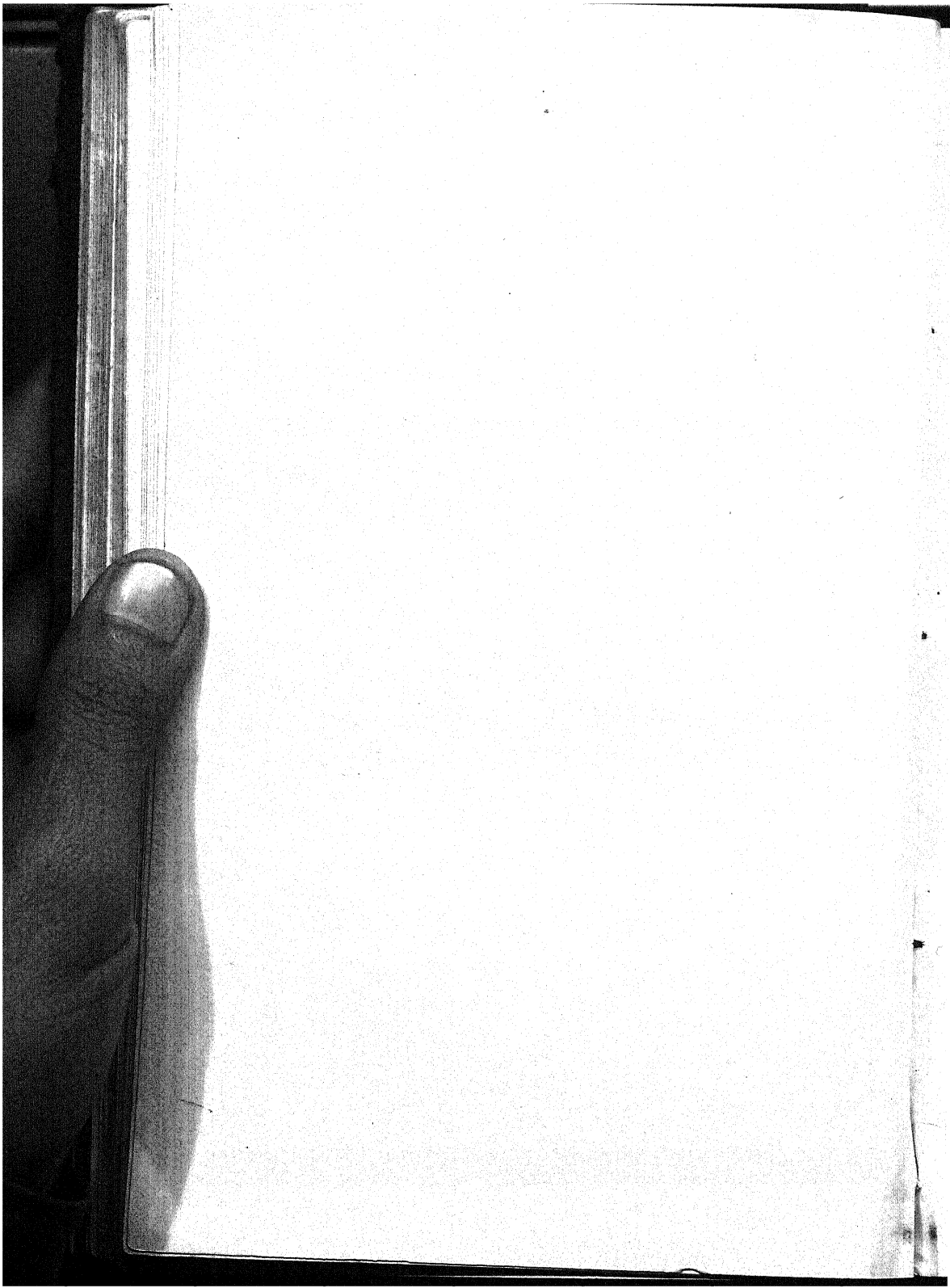


FIG. 11.—Influence of boric acid on the development of the broad-bean in culture solution. Each set receives "complete nutrients" : that to the right nothing else : the other four receive traces of boric acid (K. Warington).



New Zealand and "top rot" of tobacco have also been ascribed to boron deficiency; all are curable by small dressings of borax.[1]

Boron is also essential for cereals,[2] citrus,[3] sugar cane,[4] and tomato plants; the latter became diseased without it.[5] For soya beans it is said to be advantageous though not essential.[6]

Quantities in excess of the very small amounts needed by the plant are harmful (p. 123). F. Terlikowski and B. Nowicki [7] have made numerous analyses showing the boron content of soils, plants, and potassic fertilisers, and they have emphasised the very narrow margin between beneficial effects and injury. It is not yet safe to advise farmers to use boron except under clearly specified conditions.

Copper.

Copper is invariably present in plants, and, according to Maquenne and Demoussy,[8] it migrates to points of greatest vitality as if it played an active part in intracellular metabolism. No sign of benefit could be observed in W. E. Brenchley's water cultures, a harmful effect being produced even by 1 part of copper sulphate in 10,000,000 of water, and by the trace of copper present in ordinary distilled water. A. L. Sommer [9] and Lipman and MacKinney [10] all adduced evidence, however, that a trace of copper salt is essential for

[1] M. Mes, *Phytopath. Ztschr.*, 1930, **2**, 593; J. Kuyper, *Deli-Proefsta Flugschr.*, 1930, p. 50.

[2] A. L. Sommer and C. B. Lipman, *Plant Physiol.*, 1926, **1**, 231.

[3] A. R. C. Haas and L. J. Klotz, *Hilgardia*, 1931, **5**, 175.

[4] J. P. Martin, *Hawaii Plant. Rec.*, 1934, **38**, 95.

[5] D. R. Hoagland, *Calif. Agric. Expt. Sta. Mo. Bull.* No. 16, 1927, p. 562; D. A. van Schrevan, *Tijdschr. Plantenziekt.*, 1935, **41**, 1; E. S. Johnston and P. L. Fisher, *Plant Physiol.*, 1930, **5**, 387.

[6] G. H. Collings, *Soil Sci.*, 1927, **23**, 83.

[7] *Rocz. Nauk Roln.*, 1932, **28**, 135.

[8] *C.R.*, 1920, **170**, 87.

[9] A. L. Sommer, *Plant Physiol.*, 1931, **6**, 339.

[10] C. B. Lipman and G. Mackinney, *ibid.*, **6**, 593.

flax, barley, sunflowers, and tomatoes in water cultures : they show some very convincing photographs.

The instances where copper salts have proved beneficial to plant growth in field conditions all are associated with soils rich in organic matter.[1] In the Florida Everglades, a calcareous peat soil, marked increases in yield of various market garden and other crops followed the addition of 50 lb. per acre of copper sulphate. There are no disease symptoms : the effect appears to be a direct nutrition, and the result is the same whether the copper sulphate is applied to the soil or the leaves of the plants.[2]

Similar effects have been observed in Poland. R. Kwieckinski [3] showed that additions of copper sulphate at the rate of 40 kg. per hectare trebled the yield of oats on a peat soil. The copper sulphate had no effect on the rate of evolution of CO_2 from the peat nor on the mobilisation of potassium : on the other hand it approximately doubled the content of ammoniacal nitrogen and of water-soluble calcium. It also affected the colloidal properties of the soil.

In other cases definite physiological diseases occur unless copper salts are given. On newly reclaimed peat or moorland soil, plants are liable to turn yellow and the tops of the leaves to become white and die. The disease is well known in Holland and in Germany where a good deal of reclamation is going on, and is called " Urbarmachungskrankheit " or " reclamation disease " ; it affects especially summer cereals, sugar beets, and leguminous crops.

Grassland farming proved almost impossible on these soils ; in the second year after the grass had been sown all the grasses

[1] For a summary and full bibliography see *Imp. Bur. Soil Sci. Tech. Comm.* No. 31, 1934.

[2] R. V. Allison, O. C. Bryan, and J. H. Hunter, *Florida Agric. Expt. Sta. Bull.* No. 190, 1927 ; O. C. Bryan, *J. Amer. Soc. Agron.*, 1929, **21**, 923 ; R. V. Allison, *Proc. 22nd Int. Cong. Soil Sci.*, 1930, Comm. VI, *Subcomm. Peat Soils*, pp. 257-275. But see also O. Owen, " Effect of Copper Sulphate on Tomato Plants," *Ann. Appl. Biol.*, 1929, **16**, 430-437.

[3] *Putawy Memoirs*, 1930, **2**, 553.

disappeared with the exception of *Holcus lanatus* which was not affected. Ritzema Bos [1] showed that the disease could be cured by adding copper sulphate to the soil at the rate of 60 kg. per hectare. An unexpected result followed. The plants thus treated when attacked by the "grey speck" disease could not be cured by applications of manganese salts; the copper seemed in some way to have counteracted the manganese effect.

This curious antagonism of copper and manganese has been investigated by Hudig and his colleagues.[2]

Fruit trees are also affected. In almost all countries where citrus fruits are grown on soils containing much organic matter the trees suffer from a dying of the tips of the branches, leaves, and fruits: the disease is called "die-back" or exanthema.[3]

Anderssen [4] has described a chlorosis of fruit trees in South Africa which he attributes to deficiency of copper.

On the other hand, J. Caldwell shows that small quantities of copper sulphate inoculated into healthy plants produce chlorosis and distortion not unlike the symptoms of virus disease.[5]

Zinc.

The action of zinc salts on the growing plant aroused considerable interest a generation ago when zinc pots were used for pot culture work. Sometimes experiments were lost

[1] J. Ritzema Bos, *Tijdschr. Plantenziekt.*, 1925, **31**, 233. The subject has been developed by C. Brandenburg (*Tijdschr. Plantenziekt.*, 1933, **39**, 189, and *Angew. Bot.*, 1934, **16**, 505; C Meijer, *Versl. Rijkslandp. Proefsta*, Gronigen, 1934, A, **40**, 173; B. Rademacher, *Deut. Landesk. Ztg.*, 1935, A, **4**, 3-7.

[2] J. Hudig, C. Meyer, and J. Goodyk, *Ztschr. Pflanz. Düng.*, 1926, **8**, 14-52.

[3] For description see W. T. Swingle and H. J. Webber, *U.S.D.A. Div. Veg. Phys. Path. Bull.* No. 8, 1896. The effect of the copper is discussed by Oserkowsky and Thomas, *Science*, 1933, **78**, 315.

[4] F. G. Anderssen, *J. Pomol. Hort. Sci.*, 1932, **10**, 130.

[5] *J. Min. Agric.*, 1935, **42**, 97.

because of injury done to the plants. P. Ehrenberg [1] made a detailed investigation, and concluded that the zinc salts always acted unfavourably on the plant, but might nevertheless lead to increased growth through some indirect action of the soil.

Later work has revealed many instances of beneficial action.

Fruit and nut trees in parts of the United States, California, Northern Central Florida and elsewhere, suffer from various physiological diseases: mottling of leaf, "little leaf" or "rosette," and dying back of the growing tips. Ferrous sulphate was tried as a remedy; some samples used in large enough quantity were effective, others were not. Chandler, Hoagland, and Hibbard [2] in California observed that the purer samples were least effective, while others containing zinc sulphate as impurity acted much better. Quite independently Alben and Cole [3] of the Department of Agriculture observed that iron sulphate was successful in their small scale tests but not on the large scale; the difference was traced to the use of galvanised iron containers in the former, but not the latter case. Both sets of observers therefore tried zinc sulphate, and found that it cured the disease.

In many cases the zinc sulphate must be added to the soil, but in others it can be sprayed on the leaves. The symptoms are modified by the soil conditions and nutrient supplies, and it is not clear that they are actually due to a lack of zinc or whether the zinc has the property of inactivating some other causal agent.

Tung oil trees are liable in some conditions to a bronzing of the leaf, which is curable by treatment with zinc sulphate.[4]

[1] *Landw. Vers.-Sta.*, 1910, **72**, 15-142.

[2] W. H. Chandler, D. R. Hoagland, and P. L. Hibbard, *Proc. Amer. Soc. Hort. Sci.*, 1931, **28**, 556-560; E. R. Parker, *ibid.*, 1936, **33**, 82.

[3] A. O. Alben, J. R. Cole, R. D. Lewis, *Phytopath.*, 1932, **22**, 595 and 979.

[4] H. Mowry and A. F. Camp, *Fla. Agric. Expt. Sta. Bull.* No. 273, 1934.

In a careful series of water culture experiments A. L. Sommer and C. B. Lipman [1] found that zinc was essential to the growth of wheat, barley, buckwheat, beans, and sunflower, and was not merely prophylactic in its action.

Other Metals.

Cobalt is always present in plants,[2] but is not known to be necessary for their growth. Certain animal diseases in Australia are, however, attributed to deficiency of cobalt in the vegetation [3] and the question is also under investigation at the Cawthron Institute, New Zealand.

Aluminium is included by Mazé among the essential nutrients, and is also considered beneficial by Stoklasa [4] and Sommer.[5] In large quantities it is harmful, and it appears to be a partial cause of the injury suffered by plants on acid soils (p. 545). It reduces considerably the absorption of ammonium ions by the tissues of cut potato tubers.[6]

Molybdenum.—Miss F. M. L. Sheffield has made the curious observation that a small quantity of ammonium molybdate applied to *Solanum nodiflorum* caused its leaves to take on the appearance of being affected by one of the virus diseases, and also changed the growth of the plant from an upright into a trailing habit.[7] W. A. Roach shows that different varieties of fruit stocks differ in their ability to take up molybdenum from the soil.[8]

[1] *Plant Physiol.*, 1926, **1**, 231 ; 1928, **3**, 217.

[2] G. Bertrand and Mokragnatz, *Ann. Sci. Agron.*, 1925, **42**, 225.

[3] *E.g.* " Coast disease " in South Australia ; H. R. Marston, *Aust. J. Counc. Sci. Ind. Research*, 1935, **8**, 111 ; E. W. Lines, *ibid.*, 117 ; " Enzootic marasmus," E. J. Underwood and J. F. Filmer, *Aust. Vet. J.* 1935, **11**, 84 (this seems related to New Zealand " bush sickness ").

[4] *Biochem. Ztschr.*, 1918, **91**, 137.

[5] A. L. Sommer, *Univ. Calif. Pub. Agric. Sci.*, 1926, **5**, 57-81.

[6] G. F. Asprey, *Proc. Roy. Soc.*, 1933, B, **112**, 451.

[7] *Ann. Appl. Biol.*, 1934, **21**, 430.

[8] *Nature*, 1933, **131**, 202 ; *Ann. Appl. Biol.*, 1934, **21**, 333.

Non-metals.

The Halogens.

Chlorides.—Moderate dressings of sodium chloride are beneficial for sugar beet, mangolds, lucerne, barley and certain other crops. Tobacco increases in yield and improves in texture of leaf without detriment to combustibility so long as the chlorine does not exceed 20 lb. per acre.[1] Larger quantities of chloride increase the yield still further but lower the burning quality: still larger quantities retard growth and cause the leaves to become thick and brittle. C. Dupont [2] found that plants receiving chlorides in non-toxic quantities are greener, more turgid, and transpire less water than those receiving equivalent amounts of nitrates or sulphates; he suggests that the chloride ion enters the plant more readily than these others.

Towards the end of the plant's life, the chloride causes the leaves to die earlier, and presumably hastens maturation. This is an advantage for barley, but a disadvantage for potatoes. Cereal straw contains less dry matter when fertilised with a chloride than with a sulphate.

In larger quantities, however, the chloride ion is harmful to all crops, particularly to potatoes, which suffer both in yield and quality. Mangolds and sugar beet are considerably more tolerant.

Injury by excess of sodium chloride is a common phenomenon on alkali soils or land liable to flood.

The harmful effect of chlorides is well marked where the cation is toxic.

In natural conditions plants receive measurable quantities of chlorides (chiefly sodium chloride) in the rain, and the amount is greater in the wetter western parts of the country than in the east. At Rothamsted the amount of chlorine brought down averages 16 lb. per acre per annum and fluc-

[1] "Symposium on Tobacco Research," *J. Amer. Soc. Agron.*, 1929, 21, 113.

[2] *Ann. Sci. Agron.*, 1924, 41, 369.

tuates between 10·3 and 24·4 lb.; [1] it comes chiefly in the winter months. But nearer the sea the amounts become very high, rising, according to N. H. J. Miller's determinations in rain water from the Hebrides,[2] to—

	Annual Rainfall.	Chlorine per Acre.
	ins.	lb.
Laudale. . .	76·89	168·5
Butt of Lewis [3] .	40·57	6884
Monach . .	47·21	2723
Barrahead [4] . .	33·93	5753

Fluorides in small quantities are regarded as necessary by the Japanese and French investigators.[5]

Gautier and Clausmann [6] claim that a dressing of 5 kgms. of amorphous calcium fluoride per acre was followed by increases in cereal crops of 5 to 18 per cent., and sometimes considerably more in the case of root crops; this, however, lacks confirmation.

Iodides are also regarded as necessary by Mazé and the Japanese investigators. This question is of some practical interest since medical authorities trace a relationship between iodine and goitre in human beings, and there are also possible relationships between iodine and certain disorders of live-stock.[7] Moreover, natural Chile saltpetre contains iodine while the synthetic fertilisers do not, and much experimental work has been done to discover whether the Chile salt has therefore any additional value. The evidence is overwhelmingly against any increased crop growth following the addition

[1] E. J. Russell and E. H. Richards, *J. Agric. Sci.*, 1919, **9**, 309.

[2] *J. Scottish Met. Soc.*, 1913, **16**, 141-158.

[3] Collected at 70 feet above sea-level.

[4] Collected at 620 feet above sea-level.

[5] P. Mazé (1919); Susuki and Aso, *Bull. Coll. Agric.*, Tokyo, 1903, **5**, 473; O. Loew, *ibid.*, 1904, **6**, 161.

[6] *C.R.*, 1919, **168**, 976; and **169**, 115.

[7] J. B. Orr and I. Leitch, *Med. Res. Council Special Rept.*, 1929, No. 123. W. Godden summarises the results in *Agricultural Progress*, 1931, **8**, 81-94.

of iodine compounds.[1] Nor is the iodine content of the crop always raised by increasing the supply, and when it does enter the plant it tends to remain in the stems and leaves rather than penetrate to tubers, roots, or seeds. Crops usually contain 0·3 to 3 grms. iodine per hectare: the soil contains some 2000 to 5000 grms., while the rain brings down some 12 grms. per hectare.

Sulphur.

Sulphur is an essential constituent of plants and occurs in some quantity in the Brassica family, *e.g.* in cabbages and swedes. Omission of sulphates from the culture solution led to yellowing and brown spotting of the leaves of soy bean and brown discoloration of the roots,[2] and to a uniform chlorosis of tobacco plants, distinct from the chlorosis resulting from magnesium or potassium deficiency (pp. 84, 100). In fruit trees the effects of sulphur deficiency resemble those of nitrogen deficiency, but they are less severe.[3]

Deficiency of sulphur, like that of potassium and of phosphorus, leads to an increased percentage of amino acids in the dry matter of the plant, and a decreased percentage of protein.[4] The best-known example of a sulphur deficiency disease, however, is the "tea yellows" affecting tea plants in Nyassaland, fully investigated by Storey. As usual with deficiency diseases, the soils on which it occurs contain the deficient element in quantities which are not abnormally low: one has to assume that it is present in an unavailable form.[5]

Sulphates seem to have special value in warm, dry conditions: instances occur in California,[6] in Southern Oregon,

[1] W. E. Brenchley, *Ann. Appl. Biol.*, 1924, **11**, 86; also W. Gaus and R. Griessbach, *Ztschr. Pflanz. Düng.*, 1929, A, **13**, 321; a full and interesting summary.

[2] J. M. Ginsburg, *Soil Sci.*, 1925, **20**, 1-13.

[3] T. Wallace, *J. Pomol. Hort. Sci.*, 1925, **5**, 27.

[4] G. T. Nightingale *et al.*, *Plant Physiol.*, 1932, **7**, 565.

[5] H. H. Storey and R. Leach, "Tea Yellows Disease," *Nyassaland Dept. Agric. Bull.* No. 3, 1932; *Ann. Appl. Biol.*, 1933, **20**, 23.

[6] C. B. Lipman and W. F. Gericke, *Soil Sci.*, 1918, **5**, 81.

and in Victoria (Australia);[1] in all these cases sulphate of ammonia is better as fertiliser than nitrate of soda[2] though (on the Californian soils at any rate) it is no better than a mixture of nitrate and sulphate of soda. Superphosphate, which contains calcium sulphate, is better as fertiliser than pure calcium phosphate, and sulphate of potash better than muriate of potash for lucerne.

In moist regions also sulphates have proved beneficial: Dymond[3] showed that they increased the yield of crops rich in protein though not of cereals or pastures. The Wisconsin workers also obtained beneficial results[4] as also has F. J. Alway with lucerne in Minnesota,[5] especially where the plants contain less than 0·25 per cent. sulphur in the dry matter. Doak, experimenting with lucerne in New Zealand, found that dressings of gypsum and even of sulphur increased the percentage of sulphur in the dry matter, raising it from 0·26 per cent. to 0·4 or 0·5 per cent., and in some cases also increased the yield.[6]

Marston and Brailsford Robertson have studied the effect of sulphur compounds in plants on their feeding value to animals. They conclude that part of the sulphur assimilated by the plant is converted into cystine, the only amino-acid in which it occurs, and in their view the only substance from which animals can assimilate their sulphur. All animals require some of this, but sheep need a good deal owing to the large percentage of cystine in the keratin or fibre of wool.[7]

[1] Mary D. Glynne, *Roy. Soc. Vict.*, 1929, **42**, 30.

[2] W. W. Johnston, *Soil Sci.*, 1926, **21**, 233; W. L. Powers, *J. Amer. Soc. Agron.*, 1927, **19**, 1007, for summary of field results.

[3] T. S. Dymond, F. Hughes, and C. W. C. Jupe, *J. Agric. Sci.*, 1905, **1**, 217-229.

[4] E. B. Hart and W. H. Peterson, *Wis. Agric. Expt. Sta. Res. Bull.* No. 14, 1911; W. Pitz, *J. Agric. Res.*, 1916, **5**, 771.

[5] *Proc. 1st Int. Cong. Soil Sci.*, Washington, 1927, Comm. IV, p. 590.

[6] B. W. Doak, *N.Z. J. Sci. Tech.*, 1929, **11**, 25.

[7] H. R. Marston and T. Brailsford Robertson, *Aust. Council Sci. Indust. Res. Bull.* No. 39, 1928.

Silicon.

Great importance was attached by the older plant physiologists to silicon in the nutrition of the gramineæ, it being supposed to give strength to the straw. Field experiments at Rothamsted disproved this view, neither barley straw nor grass being strengthened by manuring with sodium silicate. But the interesting fact emerged that the silicate increased the yields of barley on plots deficient in phosphate (Table 26).

Table 26.—Effect of Silicates on the Growth of Barley, 1864-1904. Rothamsted.

	Yield of Dressed Grain, bushels.		Yield of Straw, cwts.		Ratio $\frac{\text{Total Grain}}{\text{Straw}}$.	
	Without Silicate.	With Silicate.	Without Silicate.	With Silicate.	Without Silicate.	With Silicate.
Nitrate only . .	27·3	33·8	16·2	19·8	85·1	86·6
Nitrate + phosphate	42·2	43·5	24·6	25·8	87·2	85·8
Nitrate + potassium salts . . .	28·6	36·4	17·9	21·7	80·6	85·0
Nitrate + phosphate +potassium salts	41·2	44·5	25·3	27·6	82·7	82·1

This result was later obtained for oats in water cultures by C. Kreuzhage and E. Wolff.[1] The phenomena were studied by Hall and Morison [2] who conclude that silicates act by causing an increased assimilation of phosphoric acid by the plant, the seat of action being in the plant and not in the soil. This view is controverted by O. Lemmermann [3] and R. A. Fisher [4] who suppose that the silicate simply increases the amount of phosphate available in the soil.

Both actions, however, may take place. W. E. Brenchley, E. J. Maskell, and K. Warington [5] show that the efficiency of the phosphorus is increased by addition of silicate, so that

[1] *Landw. Vers.-Sta.*, 1884, **30**, 161-197.
[2] *Proc. Roy. Soc.*, 1906, B, **77**, 455.
[3] *Ztschr. Pflanz. Düng.*, 1929, A, **13**, 28-39. A critical review.
[4] *J. Agric. Sci.*, 1929, **19**, 132-139.
[5] *Ann. Appl. Biol.*, 1927, **14**, 45-82.

the normal phosphatic effects are intensified and more tillers, more ears, and more fertile florets are produced. There is no indication of partial replacement of phosphorus by silicon; this view accords with the Hoos field experience that silicates increase the rate of deterioration of grain yield while phosphates decrease it.

Great interest has been taken in this problem both in Germany and in Japan, because it seemed at one time to open up the possibility of replacing some of the imported phosphates by home-made silicates. So far the hopes have not materialised.[1]

Titanium.

Titanium occurs in all soils and in all plants, usually to the extent of about 1 mgm. Ti per kilo of green weight. Whether it is essential to plant life is not known. Pot experiments by A. Němec and V. Káš indicated that it increased the growth of mustard, peas, and lucerne when supplied as sodium titanate or titano-citrate,[2] but Blanck and Alten[3] were unable to confirm this. No recent critical investigation has been made.[4]

Physiological Balance.

It has long been recognised that neither unicellular organisms nor higher plants can continue to live if transferred to pure water or to a solution of a single salt; the effect is more than

[1] For further information see O. Lemmermann and H. Wiessmann, *Ztschr. Pflanz. Düng.*, 1922, A, **1**, 185; Jennings, *Soil Sci.*, 1919, **7**, 201; Th. Pfeiffer, *Mitt. Deut. Landw. Gesell.*, 1923, p. 196; P. L. Gile and J. G. Smith, *J. Agric. Res.*, 1925, **31**, 247-260; W. Krüger and G. Wimmer, *Bied. Zbl.*, 1928, **57**, 414; *Ztschr. für Zückerind.*, 1927, 127-194; H. Wiessmann, *Ztschr. Pflanz. Düng.*, 1925, A, **4**, 73-83.

[2] *Biochem. Ztschr.*, 1923, **140**, 583.

[3] *J. Landw.*, 1924, **72**, 103.

[4] For a discussion of the problem see H. O. Askew, *N.Z. J. Sci. Tech.*, 1930, **12**, 173-179; Gabriel Bertrand and C. Voronca-Spirt, *C.R.*, 1929, **188**, 1199, and **189**, 73, deal with the occurrence of titanium in plants.

starvation, and amounts to positive injury, due to the movement of ions out from the plant into the solution and to other actions specific to the particular salt.[1] The plant continues to live only when its culture solution is sufficiently complex in composition.

Two sets of factors seem to be involved: the proportions of the different nutritive elements needed to ensure maximum growth, and the "antagonism" of ions in solutions.

Tottingham [2] and Shive [3] attached much importance to the ratios between the various nutrients, and drew up lists of "best," "medium," and "poor" ratios. Further experience makes it doubtful whether any "optimum" ratio exists: Hoagland [4] obtained satisfactory growth with a wide range of mixtures so long as the total supply and concentration of essential elements was adequate. The plant's power of adaptation and internal compensation enables it to grow equally well over a wide range of concentrations of the various salts.

Plants growing in soil are less sensitive to changes in the proportions of the nutritive elements than those in solution.

Adverse effects are produced when the supply of nitrate much exceeds that of potassium (p. 87); possibly also potassium and magnesium, and calcium and magnesium (p. 101) are somehow associated. In Germany considerable importance has been attached to Ehrenberg's so-called "potash lime law," [5] according to which lime reduces the amount of potassium taken up by the plant, and may therefore depress crop yields on soils poor in potassium. Gregory, Richards, and Shih show that this is true only for low levels of sodium supply

[1] For toxic effects of monopotassic phosphate and of ammonium sulphate on soya beans see J. W. Shive, *Soil Sci.*, 1918, **5**, 87, and M. I. Wolkoff, *ibid.*, 123-150.

[2] *Physiol. Res.*, 1914, **1**, 133-245.

[3] *Ibid.*, 1915, **1**, 327-397; also *J. Agric. Res.*, 1920, **18**, 357-378.

[4] *J. Agric. Res.*, 1919, **18**, 73-117; also A. R. Davis, *Soil Sci.*, 1921, **11**, 1.

[5] *Landw. Jahrb.*, 1919, **54**, 4.

and high levels of calcium. In the reverse case, where the ratio of sodium to calcium was high, further additions of calcium increased the uptake of potassium, and if the supply of potassium were low, increased the yield also.

The effect of one fertiliser is not infrequently enhanced by simultaneously supplying another: *e.g.* nitrogenous and potassic fertilisers, or nitrogenous and phosphatic fertilisers, may mutually reinforce each other's action. These interactions are studied in the new field experiments carried out at Rothamsted.[1]

Injurious Substances.

Acids and Alkalis: Hydrogen and Hydroxyl Ions.

From the fact that plants grow badly on acid or alkaline soils it has been concluded that hydrogen and hydroxyl ions are injurious. In large amounts they undoubtedly are; addition of sufficient strong acid or alkali, such as HCl or NaOH to culture solutions or soils rapidly kills plants. But the smaller intensities corresponding to the reaction values of natural soils present a more difficult problem, because changes in reaction affect some of the nutrients, especially calcium and iron, precipitating or otherwise throwing them out of action. It is uncertain, therefore, whether the harmful effects are direct actions of hydrogen and hydroxyl ions on the plant, or indirect actions arising through deficiency of some essential nutrient.

The experiments are usually made in water or sand cultures. A wide range of *p*H values can be secured by using the mono-, di- or tri-potassic or other phosphates in the nutrients.[2] Some difficulty arises from the circumstance that the absorption of nutrients by the plant causes continuous changes in the reaction of the medium; this is met by frequently

[1] For instances see the Rothamsted Annual Reports, 1930 *et seq.*

[2] For examples see D. R. Hoagland, *Soil Sci.*, 1917, **3**, 547. An alternative method, the addition of standard acid or alkali, is also used, see *e.g.* H. E. Clark and J. W. Shive, *Soil Sci.*, 1934, **37**, 203.

changing the solution, or by using large volumes, or by some buffering device.

-OH ions are more toxic than -H ions. In water cultures better growth is always obtained in acid than in neutral solu-

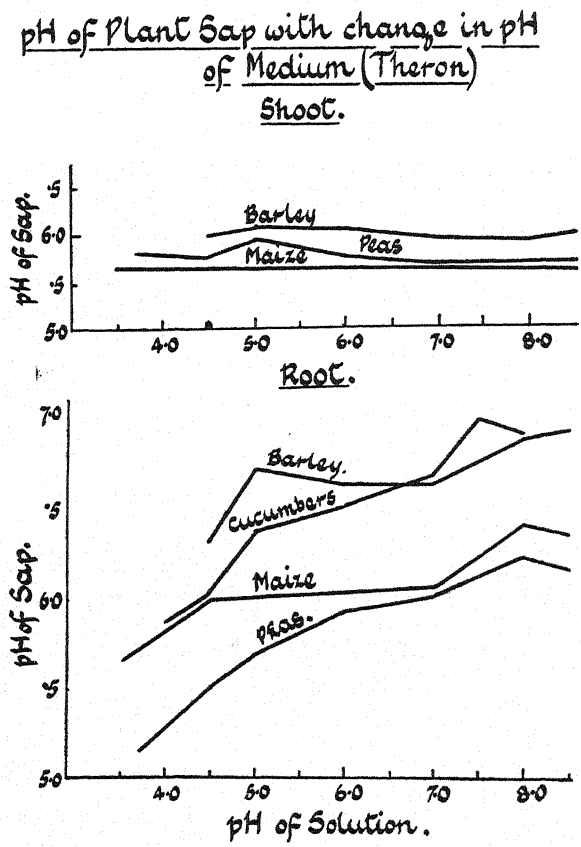


FIG. 12.—Reaction of cell sap as affected by reaction of medium. Upper curves, shoot; lower curves, root.

tions, but the optimum reaction and the degree of tolerance to the acidity depend on the composition of the medium. In Hoagland's water cultures on barley [1] the best results were

[1] *Soil Sci.*, 1917, 3, 547. See also Salter and McIlvaine, *J. Agric. Res.*, 1920, 19, 73.

obtained with *p*H about 5·2: in the Rothamsted solution the *p*H value is 3·8, while Carsten Olsen [1] obtained varying optima according to the iron compound present: for ferric citrate the optimum was about *p*H 8, and for ferric chloride *p*H 4·5 and *p*H 8 (two optima). The reaction must be such that the iron, calcium, and phosphate remain in solution, and so long as this does not require too intense an acidity the plant grows well.

In soils, on the other hand, plants make their best growth in neutral or nearly neutral conditions. Marked acidity is not necessary for ensuring supplies of nutrients, and it has effects on the soil which injuriously affect plant growth.

Variations in the acidity of the medium have no effect on the acidity of the sap of the leaf and stem or, in the case of potatoes, of the tuber,[2] but the root sap in Theron's water-culture experiments varied in reaction with the changes in reaction of the solution [3] (Fig. 12).

Usual values for the *p*H values of the sap of plants are 5·5 to 6·5. The roots of leguminous plants frequently, but not always, have a less acid sap than those of non-leguminous plants in similar conditions.[4] The acidity of the root sap tends to decrease as the nitrogen supply increases.[5]

Metallic Salts.

Complaints are sometimes made by farmers in mining districts that their crops suffer damage from the waste products—generally metallic salts—turned into the streams from the works, especially where the water is wanted for irrigation, or where, as in Japan, rice is grown in the marshes. The damage done to pastures by the lead mines of

[1] *C.R. Lab. Carlsberg*, 1935, **21**, 15.

[2] I. M. Robertson and A. M. Smith, *Biochem. J.*, 1931, **25**, 763 (potato tubers).

[3] *Calif. Pub. Agric. Sci.*, 1924, **4**, 413.

[4] H. Kappen, *Landw. Vers.-Sta.*, 1918, **91**, 1-40; W. Thomas, *Plant Physiol.*, 1930, **5**, 443.

[5] W. H. Pearsall and J. Ewing, *Ann. Bot.*, 1929, **43**, 27.

Cardiganshire has been investigated by J. J. Griffith [1] at Aberystwyth. Clover is particularly susceptible. A heavy dressing of lime proved a useful remedy.

Smelting works are a common source of harmful substances in the surrounding soil. A striking investigation was made by Schucht [2] of the soils surrounding an isolated smelting works which had been in operation for some 400 years. The top 20 cms. of soil in an area of about 15 sq. kms. (approximately 3·6 million tons) contained more than 900 tons of zinc, 600 tons of arsenic, 800 tons of lead, and nearly 200 tons of copper. The quantities rapidly decreased as the distance from the works increased, but there was no evidence that the vegetation was actually suffering. Grazing animals, however, are liable to suffer, and smelting works are frequently presented with claims for damage to livestock.[3]

Zinc also causes injury in parts of Wales.[4]

Copper salts do not appear to be anything like so toxic in the soil as in water culture.[5]

Manganese Salts.

Certain Hawaiian soils contain sufficient manganese salts to injure pine-apples, stunting the roots and causing chlorosis of the leaves. The symptoms are described by E. V. Wilcox and W. P. Kelley; [6] the effect is attributed to the manganese interfering with the iron in the plant.[7]

Ferrous salts are toxic, and are commonly regarded as one cause of the sterility of badly aerated soils.

[1] *J. Agric. Sci.*, 1919, **9**, 366.

[2] F. Schucht, H. H. Baetge, and M. Düker, *Landw. Jahrb.*, 1932, **76**, 51.

[3] See J. T. Dunn and H. C. L. Bloxam, *J. Soc. Chem. Indust.*, 1932, **51**, 100 T.

[4] A Flintshire garden soil examined at Rothamsted contained 0·78 per cent. of zinc. It proved, as might be expected, highly infertile.

[5] Russell and Darbishire, *J. Agric. Sci.*, 1907, **2**, 305.

[6] *Hawaii Bull.* No. 28, 1912. See also W. T. McGeorge, *Soil Sci.*, 1923, **16**, 269.

[7] A. Rippel, *Biochem. Ztschr.*, 1923, **140**, 315.

Aluminium salts have been much studied as one of the causes of the injury in acid soils [1] (see p. 545).

Chromium and nickel are regarded as the cause of infertility of certain soils in the United States.[2]

Whenever infertility is traced to any of these metallic salts a good dressing of lime is usually found to be an effective antidote.

Non-metals.

Boron compounds, brought down from the mountains by the water used for irrigation, have injured citrus and walnut trees in Southern California, causing a yellowing and dying of the leaves. Normal leaves contained less than 100 parts of boron per million of dry matter: injured leaves contained 360 to 1100 parts per million.[3]

Tobacco and tomatoes are particularly sensitive to the presence of boron.[4]

Selenium is absorbed from soils containing it, and although it does not apparently injure the plant it can cause considerable harm to animals feeding thereon. This was first observed in South Dakota: grain and other vegetation grown in certain regions produced in animals toxic symptoms different from those of fluorine, lithium or oxalic acid. Selenium was suggested as a possible cause and found. A detailed investigation by H. G. Byers [5] showed that extensive areas of cretaceous shales in the dry Western States were rich in selenium which passed into the plants in sufficient quantities to injure animals.

[1] Some of the earlier work was vitiated by the circumstance that the possibility of phosphorus starvation was not eliminated. This objection has been overcome in the more recent studies of W. H. Pierre and others, *Soil Sci.*, 1932, **34**, 145 and 307.

[2] W. O. Robinson, G. Edgington, H. G. Byers, *U.S.D.A. Tech. Bull.* No. 471, 1935.

[3] W. P. Kelley and S. M. Brown, *Hilgardia*, 1928, **3**, 445. For the effects on acid soils see J. S. McHargue, *J. Agric. Res.*, 1923, **24**, 781.

[4] F. Terlikowski and K. Miłkowski, *Rocz. Nauk Roln.*, 1933, **31**, 201.

[5] *U.S.D.A. Tech. Bull.* No. 482, 1935.

Substances Injurious only in Large Quantities.

Calcium Carbonate.

In large quantities calcium carbonate injures certain crops so much that they will not grow. The effect is apparently indirect, due partly to precipitation of the iron so that plants become chlorotic, partly also to a whole series of changes in chemical and physical properties of the soil resulting from the presence of so much calcium carbonate. It is discussed on pages 593 *et seq.*

Magnesium Carbonate.

Tenant (1799) in studying the alleged harmful effects of certain limestones found near Doncaster, concluded that magnesium carbonate is toxic to plants, and many agriculturists accept this view. Modern investigations [1] on magnesian limestone, however, have failed to show any harmful effect; indeed, in the Woburn experiments Voelcker [2] has obtained an actual benefit on wheat using magnesia (MgO) so long as the quantity used was not too large. But the soluble salts, the sulphate and especially the chloride, are harmful.

Cases are reported by Loew where insoluble magnesium compounds have caused infertility; none, however, have fallen under the writer's observation in this country. The soil of the Greenville Experimental Farm, Utah, is rich in magnesia—containing over 6 per cent. of MgO—and is remarkably fertile. It also contains, however, 17 per cent. of CaO and 20 per cent. CO_2.[3] Various infertile soils derived from basic rocks rich in magnesia, the infertility of which had been attributed to the excess of magnesia, proved on examina-

[1] See, *e.g.*, J. G. Lipman, H. C. McLean, A. W. Blair, and L. F. Merrill, *New Jersey Bull.* No. 267, 1914, and on the other side, D. A. Gilchrist, *Durham Coll. Bull.* No. 12, 1915.

[2] *J. Roy. Agric. Soc.*, 1910, **71**, 343.

[3] J. E. Greaves, R. Stewart, and C. T. Hirst, *J. Agric. Res.*, 1917, **9**, 301.

tion to contain comparatively large amounts of easily soluble and available chromium and nickel to which the infertility might reasonably be attributed.

Soluble Salts in Alkali Soils.

Over great areas of the world, where the average rainfall is less than 15 inches per annum, the soil is liable to contain appreciable amounts of soluble salts, notably sodium carbonate and the chlorides and sulphates of magnesium, sodium, potassium, and calcium. Some of these (particularly the chlorides) may directly injure the plant; others apparently interfere with the supply of water or of nutrients.

The qualitative effect of these salts on plants growing in natural conditions is to give them a dull colour and to cause a waxy deposit on the surface of the leaves. Numerous investigations on the toxic limits have been made in the Western States and elsewhere; the figures differ widely, partly because they are affected by so many factors, partly because of the difficulty of measuring injury. In dilute solutions these salts stimulate germination, growth, and transpiration; in more concentrated solution they cause injury; and, in still more concentrated solutions, death. Plants differ in their sensitiveness, maize being very sensitive. Those less affected include sugar beet, barley, lucerne, and sweet clover (*Melilotus alba* and *offic.*), which are therefore grown in cool alkali regions; and sorghum, cotton, rice, berseem and, least sensitive of all, the date palm, which can be grown in warm alkali regions.

Some of the wild plants are remarkably tolerant of soluble salts: *Atriplex*, common in most hot, dry regions and *Kochia* (Australian grey bush), may contain in their dry matter 35 per cent. or more of ash, most of which is a sodium salt.[1] For individual plants the injury depends on their age, being greatest for seedlings and least for adults; much of the successful management of alkali soils depends on nursing the

[1] See J. G. Smith, *U.S.D.A. Yrbk.* for 1898, 535, and H. C. Trumble, *Austr. J. Coun. Sci. Indust. Res.*, 1932, **5**, 152.

plants through their early growth by some device such as washing out the salts from the surface layers. Some plants are more tolerant than others in early stages; for this reason sweet clover is at times preferred to lucerne because it starts growth more readily in presence of salts.

The effect is also much modified by other salts, notably calcium salts, so that a harmful concentration of sodium chloride may become innocuous if calcium sulphate is added. The nature of the medium also affects the result; plants suffer more in water cultures than in sand and more in sand than in soil from a given concentration of a salt.

Sodium carbonate is the worst of the alkali salts, not, however, because it is most toxic, but because it produces harmful effects on the soil, thus intensifying the general injury to the plant. Sodium chloride is about equally harmful in water or sand culture where this soil effect is eliminated, and according to B. C. Buffum [1] sodium and potassium sulphates and chlorides are all equally harmful at the same osmotic pressure. At two atmospheres (0·27 per cent. NaCl) they stimulated germination and growth; at 7·1 atmospheres (0·97 per cent. NaCl) they caused injury.[2]

Plant Appearances as Diagnostic of External Conditions.

From the foregoing pages it is possible to construct a table—at present only very incomplete—indicating the appearances in the growing plant corresponding with certain external conditions. The appearances vary in detail with different plants and combinations of conditions; many of them are not easily described, and if they are to be used in any but a general way they should be studied by setting up the appropriate vegetation experiments. The Rothamsted plots are rich in examples: faithful pictures of characteristic

[1] *Wyoming Bulls.* No. 29 (1896) and No. 39 (1898), and Reports, 1899 and 1900.

[2] For summary of literature see F. S. Harris, *Soil Alkali.* Wiley, New York, 1920.

plants have been painted and stored in the library. At Bernburg plants have been grown in pot culture and the appearances recorded by colour photographs.[1] Fruit trees have been studied in detail by T. Wallace at Long Ashton.[2] Further references and details will be found in the preceding pages under each factor.

THE LEAF.

Poor leaf growth.		
(1) *Dwarf plants.*	Yellowish colour.	Lack of nitrogen.
	Greyish colour.	Lack of phosphate or potassium.
	Glaucous appearance.	Difficulty of obtaining water, excess of soluble salts, etc.
(2) *Tall spindly plants.*		Lack of light near soil.
		Plants closely packed.
(3) *Fruit trees.*	Yellow, orange, or reddish, usually with reddish spots.	Lack of nitrogen or of sulphur (all English fruits).
	Dull purple, changing to bronze colour, often with purple or brownish spots.	Lack of phosphorus (all English fruits).
	Dull green, brown or greyish edge scorch.	Lack of potassium.
	Bronze colour.	Lack of potassium.[3]
	Yellowish, poor growth, premature defoliation.	Competition of grass and other herbage.
Chlorosis, or yellowing of leaf.	Uniform all over the leaf.	Lack of iron.
		Excess of calcium, magnesium, sodium or potassium carbonates.[4]
		Excess of manganese.
		Lack of manganese[5] or of copper.
		Lack of sulphur (tobacco)
	Patchy, spreading from midrib outwards.	Lack of magnesium.
	Mottled.	Lack of calcium or of zinc (citrus).

[1] These are reproduced in *Ztschr. Ver. Deut. Zuckerindust.*, 1927; *Mitt. Anhalt. Vers.-Sta. Bernburg*, 60-65.

[2] Results published in *J. Pomol. Hort. Sci.*, 1925, **4**, 117; *Ann. Appl. Biol.*, 1930, **17**, 649; 1934, **21**, 322.

[3] H. S. Reed and A. R. C. Haas, *Calif. Agric. Expt. Sta. Tech. Paper* No. 11, 1923 (orange trees); T. Wallace (gooseberry, strawberry, raspberry).

[4] See C. B. Lipman, *Soil Relationships and Citrus Chlorosis; Phytopathology*, 1921, **11**, 301-306.

[5] But see C. Olsen, *C.R. Lab. Carlsberg*, 1934, **20**, No. 2.

THE LEAF—*continued.*

	Spotty or interveinal.	Lack of potassium.
	Leaf yellowing and then scorching at tip and from edges inwards.	Lack of potassium (cereals, tomatoes, fruit), or of calcium (apples).
	Leaf yellowing and dying from midrib outwards.	Lack of nitrogen.
Patches on leaf.	Brown patches resembling scorch (fruit trees).	Lack of potassium.
	Brown patches chiefly in centre.	Lack of magnesium.
	Brown spots.	Lack of calcium or of phosphorus.[1]
Premature defoliation.		Lack of potassium,[2] magnesium, calcium, nitrogen, phosphate.
Rich green leaves and large thick stems.		Large supply of nitrogen.
Dark coloured leaves, tendency to crinkle.		Insufficient potassium in relation to nitrogen.
Patchy appearance of herbage, some dark green, some lighter.		Acidity of soil.
Brittle leaf and rosetting of foliage.		Lack of zinc.

Root.

Very stunted.	Acidity. Lack of calcium or phosphate: bad aeration: lack of drainage: clay soil.
Much fibrous development.	Good aeration: sandy soil.

Fruit.

Brilliant red (apples).	Lack of nitrogen. Competition of grass.
Blotchy (tomatoes). Immature appearance.	Lack of potassium.
Chlorotic appearance of ground colour.	Lack of nitrogen or iron.
Dull bronze colour.	Lack of phosphorus.

Seed.

Delayed ripening.	Excess of water: excess of nitrogen: lack of phosphate.
Failure to reach maturity.	Great lack of potassium.

[1] A. R. C. Haas, *Soil Sci.*, 1936, **42**, 93 (citrus); T. Wallace, English fruit trees.

[2] Wallace points out that the defoliation resulting from lack of potassium or of calcium usually begins at the tips of the shoots and proceeds downwards, so that the older leaves stay on longer. Defoliation from lack of other elements begins at the base of the shoot, so that the older leaves fall off first.

Possible Stimulating Effects of Radium Emanations.

Rocks and soils contain measurable amounts of radioactive substances: the following are usual quantities found per gram :—

	Radium, grms.	Thorium, grms.
Sedimentary rocks [1] . . .	$1{\cdot}4 \times 10^{-12}$	$1{\cdot}6 \times 10^{-5}$
Basic rocks [1] (basalts) . .	$1{\cdot}19 \times 10^{-12}$	$0{\cdot}8 \times 10^{-5}$
Acid rocks [2] (granites) . .	$3{\cdot}34 \times 10^{-12}$	$2{\cdot}81 \times 10^{-5}$

Moreover, the potassium compounds of the soil are radioactive (emitting, however, β-rays only),[3] and owing to the large amount their total activity is comparable with that of radium and thorium.

In addition, the soil air contains radium emanations of the order of 163×10^{-12} curies per litre at a depth of 50 cms., this being many thousand times greater than the amount found in atmospheric air; these have been studied in detail by L. B. Smyth.[4]

Many experiments have been made to discover whether the rays or emanations have any effect on the growth of plants or micro-organisms.

Some degree of stimulation of various processes has been claimed from time to time, but no clearly proved increase in plant growth has yet been obtained. So far as present evidence goes, the " radioactivity " periodically offered to farmers as a fertiliser is worthless.

[1] A. L. Fletcher, *Phil. Mag.*, 1912, **23**, 279; J. H. J. Poole, *ibid.*, 1915, **29**, 483.

[2] J. H. J. Poole and J. Joly, *ibid.*, 1924, **48**, 819.

[3] A. Holmes and R. W. Lawson, *Nature*, 1926, **117**, 620.

[4] L. B. Smyth, *Phil. Mag.*, 1912, **24**, 632.

Change in Reaction Induced by the Growing Plant.

Physiological Acidity and Alkalinity.

In the earliest systematic investigations of plant nutrition in culture solutions it was found that, during the growth of plants, nitrate solutions became progressively more alkaline until the plants suffered from chlorosis and died;[1] while on the other hand solutions of ammonium salts became increasingly acid.[2] It was suggested that the plants took up more acid than base from the nitrate and more base than acid from the ammonium salt. In 1881 A. Mayer[3] in discussing some of the erratic results obtained with potassic fertilisers suggested that the preferential uptake of potassium by plants might produce acidity in the same way as with ammonium salts. He introduced a classification of fertilisers into—

(1) Physiologically acid, *e.g.* ammonium and potassium salts.

(2) Physiologically neutral, *e.g.* calcium and magnesium sulphates, superphosphates and calcium chloride.

(3) Physiologically alkaline, *e.g.* Chile nitrate, calcium carbonate, lime.

The use of these terms was gradually extended to include other phenomena, such as the loss of calcium and the increase in acidity of field soils, but it has been shown by H. Kappen and others[4] that the effects on soil involve many other factors and cannot properly be estimated from the effects of plants in culture solutions. In arable soils acidification by ammonium salts is primarily due to nitrification, but the term physiological acidity may be retained if it is extended to include the removal of ammonium by micro-organisms as well as by plants. Nitrates undoubtedly conserve soil bases and reduce soil acidity and may correctly be termed physio-

[1] W. Knop, *Landw. Vers.-Sta.*, 1861, **3**, 295.
[2] F. Rautenberg and G. Kühn, *ibid.*, 1864, **6**, 358.
[3] A. Mayer, *ibid.*, 1881, **26**, 77; *J. fur Landw.*, 1864, **12**, 107.
[4] H. Kappen, "Die Bodenazidität," Berlin, 1929.

logically basic in Mayer's sense. Potassium salts have no appreciable effect on soil reaction and are not physiologically acid in this wider sense, although in culture solutions and in sand the acidity produced by growing plants may be measured or used to increase the availability of relatively insoluble phosphates.[1] Mayer correctly regarded superphosphate as physiologically neutral in spite of the acidity of its solutions, but many later writers erroneously assumed that superphosphate increased soil acidity. Alkaline materials, such as lime or basic slag, should not be described as "physiologically" basic.

Excretions of Nitrogen and Mineral Substances from the Roots.

In the foregoing pages we have dealt only with the uptake of elements by the roots, and this is the main process during the active growing period of the plant. Later on in the life of the plant, however, the reverse process takes place and some of these same elements are excreted from the roots. The general fact has been known for a long time. H. Wilfarth, H. Römer, and G. Wimmer [2] observed considerable loss of potassium, nitrogen and phosphorus from the roots of cereals towards the end of the ripening process. J. S. Burd in California [3] showed losses of potassium and nitrogen in barley during the time when the heads were developing, though there was a further absorption later on. In F. Sekera's [4] experiments potassium and nitrogen were both lost but only when these had been supplied in relative excess. On the other hand F. Knowles and J. E. Watkin [5] observed loss of potassium, calcium, and

[1] D. N. Prianischnikow, "Die Düngerlehre," Berlin, 1923; *Ztschr. Pflanz. Düng.*, 1933, A, **30**, 38.

[2] *Landw. Vers.-Sta.*, 1905, **63**, 1-70.

[3] *J. Agric. Research*, 1919, **18**, 51.

[4] *Ztschr. Pflanz. Düng.*, 1928, B, **7**, 533.

[5] *J. Agric. Sci.*, 1931, **21**, 612, A. E. V. Richardson, Trumble and Shapter (*Aust. Counc. Sci. Indust. Res. Bull.* No. 66, 1932) showed losses of potassium, but not of nitrogen or phosphate, from the grass *Phalaris tuberosa*.

chlorine, but not of nitrogen. Sugar beet, on the other hand, lost phosphate and chlorine but not potassium or calcium.[1]

The subject has been systematically investigated by N. T. Deleanu and his colleagues in Bucharest,[2] who show that this "negative migration" from leaves to soil occurs in all plants, whether annuals, biennials, or perennials, that all elements take part in it. The losses in their experiments are much higher than are recorded by any of the other investigators. The loss from the leaves of oats amounted to 64 per cent. of the mineral matter and 47 per cent. of the nitrogen. For wheat the losses were less [3] though they were still marked for potassium and calcium. Apparently mineral and nitrogenous compounds in the leaves in excess of what is required for grain formation are moved back to the root but instead of remaining there they

TABLE 27.—QUANTITIES OF POTASH (K_2O) FOUND IN WHEAT AT VARIOUS STAGES OF ITS GROWTH. V. G. BOSSIE.

Field Experiment.

Days from beginning of Experiment.	K_2O mgm. in Tops of 100 Plants.	K_2O mgm. in Roots of 100 Plants.
9	1817	41
14	2383	70
26	3485	94
35	3298	95
43	3020	113
52	2381	72
61	1869	—

The experiment began when the mean shoot height was 200 mm. (18th April, 1931), and it shows that the potassium lost from the tops of the plants during the later stages of growth does not accumulate in the roots, but probably passes into the soil.

[1] F. Knowles, J. E. Watkin, and Hendry, *J. Agric. Sci.*, 1934, **24**, 368.

[2] *Trav. Inst. Bot. Genève*, 1908, and later papers: especially *Bull. Soc. Sci. Cluj.*, Roumania, 1931, **6**, 209 (with M. Andreesco), also in *Beitr. Biol. Pflanz.*, 1934, **19**, Heft 3; *Acad. Roma mem. Sect. Stiint*, 1934, **9**, Mem. 10 (with C. Bordeianu). Short but good summaries are given by Miss Penston in *Nature*, 1935, **136**, 268, and 1936, **137**, 464.

[3] V. G. Bossie, *Lab. Chim. Anal. Fac. Farm.*, 1934; No. IV. in the series.

are excreted. The action is probably of considerable importance in relation to the effect of growing plants on soils.

Quantitative Studies of Plant Growth.

In recent years attempts have been made to find mathematical expressions for the relationships between the amounts of the various factors present and the amounts of plant growth.

Two general methods are adopted :—

(1) A hypothesis is set up which seems to fit the facts ; it is expressed by an equation and this is then applied to the experimental data.

(2) The experimental data are studied by statistical methods and an empirical equation or regression formula is fitted thereto, with no assumption or hypothesis as to the underlying causes.

The discussion and interpretation of the results has been greatly aided by a few fruitful conceptions.

(1) *The Law of the Minimum.*—As already pointed out Liebig supposed that the amount of plant growth was regulated by the factor present in minimum amount and rose or fell according as this increased or decreased in amount. Later work showed that this simple proportionality does not hold, but Mitscherlich modified the statement so as to bring it more closely into agreement with the facts while still retaining a simple mathematical expression. This has been used chiefly in studying plant nutrients.

(2) *Limiting Factors.*—F. F. Blackman introduced this idea to express the fact that increasing the supply of one factor may cause further increases in plant growth, but only up to the point when some other factor becomes insufficient. Further increases then lead to no more growth until the other deficiencies are supplied.

(3) *Potentials and Resistances.*—Maskell introduced the conception of regarding the various processes in plant growth as potentials, and the external factors as resistances. This

permits of mathematical treatment and is being followed up at Rothamsted.

(*a*) *Plant Nutrients.*

Of the six factors concerned, plant nutrients are, on the whole, the easiest to study quantitatively. The first good experimental investigation was made by Hellriegel in the 'eighties of the last century. Barley was grown in pots of sand, all necessary factors were amply provided, excepting only one nutrient salt, the amount of which varied in the different pots. The weights of dry matter formed are shown in Table 28 :—

TABLE 28.—EFFECT OF NITROGENOUS FOOD SUPPLY ON THE GROWTH OF BARLEY IN SAND CULTURES. HELLRIEGEL AND WILFARTH (1888).

Milligrams of nitrogen supplied	0	56	112	168	280	420
Dry matter in crop, grams	·742	4·856	10·803	17·528	21·289	28·727
Increased yield for each extra 56 mgms. nitrogen	—	4·114	5·947	6·725	1·880	2·975
Grain, per cent. of dry matter in crop	11·9	37·9	38	42·6	38·6	43·4
Weight of one grain, mgms.	19·5	30	33	32	21	30

EFFECT OF POTASSIUM SALTS ON GROWTH OF BARLEY. HELLRIEGEL AND WILFARTH (1888).

Mgms. of K_2O per pot	0	23·5	47	70·5	94	188	282
Dry matter formed when							
KCl was given	2·271	5·414	9·024	9·963	15·322	21·246	24·417
K_2SO_4 ,,	2·549	5·140	5·283	13·363	14·768	21·593	23·774
KNO_3 ,,	—	4·552	6·621	9·949	14·576	21·499	24·206
KH_2PO_4 ,,	—	4·687	6·346	9·931	12·377	17·171	—
K_2HPO_4 ,,	—	—	6·684	—	11·736	20·255	—
Average	2·410	4·948	6·791	10·801	13·755	20·357	24·132

The results for varying nitrogen supply are plotted on Fig. 13. The first increment of nitrogen produces a certain increase in

yield; but the second and third increments produce proportionately more, thus giving a greater return than is expected if, as Liebig assumed, the effect be simply proportional to the amount present. The fourth and fifth increments, however, produce less effect. The curve, therefore, resembles an S and is described as sigmoid; this is a common shape for curves showing total growth made after the lapse of a definite period of time, though perhaps less common for curves relating to environmental factors. The results for potassium also give a sigmoid curve; this is confirmed by the later

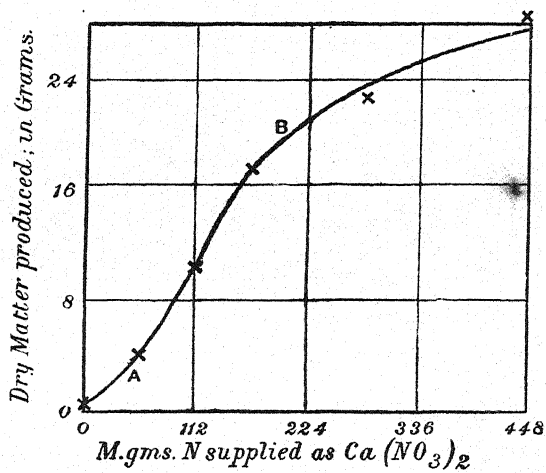


FIG. 13.—Effect of nitrogenous food supply on the growth of barley (Hellriegel).

figures of H. Wiessmann.[1] Field experiments lead to similar results: those obtained on the Broadbalk wheatfield at Rothamsted over an average of the fifty-six years, 1852-1907, are :—

	Plot 5.	Plot 6.	Plot 7.	Plot 8.
Nitrogen supplied in manure, lb. per acre .	0	43	86	129
Total produce (straw and grain), lb. per acre	2315	3948	5833	7005
Increase for each 43 lb. nitrogen . . .	—	1633	1885	1172

[1] H. Wiessmann, *Ztschr. Pflanz. Düng.*, 1923, A, **2**, 1-79.

Other experiments do not always give sigmoid curves, but a simpler shape showing a continuous fall in effect of the nutrient, the first increment producing the largest effect and subsequent increments less and less effect till finally no additional gain and sometimes even disadvantage ensues.

Whether the sigmoid or the continuously falling curve more nearly represents the normal effect of nutrients on plant growth is not known. It is possible that the curve is usually sigmoid, but the point of inflection is so near the origin that it is commonly missed.

The smoothness of the curve suggests that it can be expressed by a mathematical equation, and several investigators have attempted to do this. Among the first was E. A. Mitscherlich, who proceeded in the following manner. If all the conditions were ideal, a certain maximum yield would be obtained, but in so far as any essential factor is deficient there is a corresponding shortage in the yield. The yield rises if some of the lacking factor is added, and goes up all the further the lower it had previously fallen. Mitscherlich put this as follows: the increase of crop produced by unit increment of the lacking factor is proportional to the decrement from the maximum. The advantage of this form is that it can be expressed mathematically :—

$$\frac{dy}{dx} = (\mathrm{A} - y)\mathrm{C},$$

where y is the yield obtained when $x =$ the amount of the factor present, A is the maximum yield obtainable if the factor were present in excess, this being calculated from the equation, and C is a constant. On integration, and assuming that $y = 0$ when $x = 0$,

$$y = \mathrm{A}(1 - e^{-cx}).$$

Mitscherlich's experiments were made with plants grown in sand cultures supplied with excess of all nutrients excepting the one under investigation. Table 29 shows the results

TABLE 29.—YIELD OF OATS WITH DIFFERENT DRESSINGS OF PHOSPHATES. MITSCHERLICH.[1]

P_2O_5 in Manure.	Dry Matter Produced.	Crop Calculated from Formula.	Difference.	Difference Expressed in Terms of Probable Error.[2]
Grams.	Grams.	Grams.		
0·00	9·8 ± 0·50	9·80	—	—
0·05	19·3 ± 0·52	18·91	− 0·39	− 0·8
0·10	27·2 ± 2·00	26·64	− 0·56	− 0·3
0·20	41·0 ± 0·85	38·63	− 2·37	− 2·8
0·30	43·9 ± 1·12	47·12	+ 3·22	+ 2·9
0·50	54·9 ± 3·66	57·39	+ 2·49	+ 0·7
2·00	61·0 ± 2·24	67·64	+ 6·64	+ 3·0

obtained with oats and monocalcic phosphate. Mitscherlich claims to show by experiment that the proportionality factor C (called "Wirkungswert," or "faktor" in Mitscherlich's papers) is a constant for each fertiliser, independent of the crop, the soil, or other conditions. If this were so an experimenter knowing its value, could, from a single field trial, predict the yields obtainable from any given quantities of the fertiliser, a result of great practical value. Further, it would be possible to estimate by direct pot experiment the amount of available plant food in a soil, one of the most difficult of all soil problems. Mitscherlich, indeed, used his formula for this purpose,[3] and in his very interesting *Bodenkunde* he applies the expression in a variety of ways. Prescott also used the formula for calculating the most profitable size of dressing of superphosphate for the wheat crop in Australia.[4]

Mitscherlich's work has been extraordinarily stimulating: it caused a veritable flood of controversy and the output of papers on the subject has been colossal.

[1] *Landw. Jahrb.*, 1909, **38**, 537.

[2] If this figure is less than 3, the agreement is considered satisfactory.

[3] In "Die pflanzenphysiologische Lösung der chemischen Bodenanalyse" (*Landw. Jahrb.*, 1923, **58**, 601-617).

[4] "Law of Diminishing Returns in Agricultural Experiment," *Economic Record*, 1928, 4.

Pfeiffer [1] points out that the curves must be profoundly modified by other factors influencing plant growth, while Fröhlich took exception to the method of calculating the result. In England, Briggs has seriously criticised Mitscherlich's whole treatment of the problem.[2] In Germany, Rippel [3] has been one of his most drastic critics.

B. Baule [4] recognised these criticisms, and modified the expression while retaining the fundamental assumption. He supposes that each of the factors influencing plant growth acts in accordance with Mitscherlich's assumption, and that the final yield is the product of all the separate expressions. The yield then becomes

$$y = A(1 - e^{-c_1 x_1})(1 - e^{-c_2 x_2})(1 - e^{-c_3 x_3}), \text{ etc.}$$

The efficiency of the nutrient or other factor, called by Baule the " Wirkungsmenge," is then expressed by

$$h = \frac{\log_e 2}{c} = \frac{0{\cdot}7}{c}$$

where c = Mitscherlich's " Wirkungsfaktor." [5]

[1] Th. Pfeiffer, E. Blanck, and M. Flügel, " Wasser und Licht als Vegetationsfaktoren und ihre Beziehungen zum Gesetze von Minimum " (*Landw. Vers.-Sta.*, 1912, **76**, 169-236. See also *ibid.*, 1915, **86**, 45, and 1916, **88**, 445).

[2] *Ann. Bot.*, 1925, **39**, 475-502.

[3] A. Rippel, " Wachstumsgesetze bei höheren und niederen Pflanzen," P. Datterer, Freising, München, 1925. *Cf.* A. Rippel and R. Meyer (*Ertragsgesetz gegen Wirkungsgesetz*), *Ztschr. Pflanz. Düng.*, 1929, A, **14**, 1. See also H. Niklas and M. Miller, *Fortschr. Landw.*, 1929, **4**, 681, and *Ztschr. Pflanz. Düng.*, 1930, A, **15**, 193.

[4] *Landw. Jahrb.*, 1918, **51**, 363 ; 1920, **54**, 493.

[5] The " Wirkungsmenge " is defined as the amount of the factor needed to give half of the maximum yield obtainable by increasing the factor under consideration, all other factors remaining constant ;

$$x = h, \text{ when } x \text{ is such that}$$
$$y = \tfrac{1}{2}A$$
$$\text{then } 1 - e^{-ch} = \tfrac{1}{2}$$
$$\text{and } h = \frac{\log_e 2}{c} = \frac{0{\cdot}7}{c}.$$

K. A. Bondorff [1] took account of a possibility that Mitscherlich had until then disregarded. When any factor is present in excess it injures plant growth: Bondorff supposes that this harmful effect has not suddenly come into play but that it always operates, only it is masked in the earlier stages by the beneficial action. The final yield is thus the difference between the beneficial and the harmful effects and the equation becomes

$$y = cx^m - kx^n + a,$$

y being the yield, x the amount of factor, c, k, m and n being constants, and a the yield when none of the factor is present.

cx^m expresses the beneficial effect and kx^n the harmful effect of the factor. For most experiments with fertilisers $m = 1$: sometimes, however, it is greater than 1 and the curve is then sigmoid; for temperature and light it usually is so. Mitscherlich [2] has recognised the necessity for taking account of the harmful effect and has modified his original equation as follows:—

Starting from

$$\frac{dy}{dx} = (A - y)c \qquad \text{(p. 136)},$$

$\frac{dy}{dx}$ is the increase in yield *measured by weight* due to the addition of unit increment of fertiliser.

$\frac{1}{y}\frac{dy}{dx}$ is the increase in yield *measured as a fraction of the whole yield, i.e.* it is the relative increase in yield.

Then $$\frac{1}{y}\frac{dy}{dx} = \frac{(A - y)c}{y}.$$

Mitscherlich assumes that the harmful effect of the fertiliser on this relative increase in yield is proportional to the

[1] *Nord. Jordbr.-forskn.*, 1923, **5**, 136; and *Kongl. Vet. og Landb. Aarsskrift.*, 1924, p. 293 (French summary).

[2] *Ztschr. Pflanz. Düng.*, 1928, A, **12**, 273-282.

amount of fertiliser present: he therefore introduces the term $2kx$ to allow for it:—

$$\frac{1}{y}\frac{dy}{dx} = \frac{(A - y)c}{y} - 2kx.$$

On integration this becomes

$$y = A(1 - 10^{-cx})10^{-kx^2}.$$

Mitscherlich calls this contant "k" the "Schädigungsfaktor" or "Factor of injury" for the fertiliser: c as before is the "Wirkungsfaktor."

In this form the equation is a useful approximation to the case where one factor only varies, all others being constant. It still ignores, however, the point of inflexion which accurate working often reveals (p. 135). A simpler form of fitting the equation has been described by C. A. Farden and O. C. Magistad.[1]

Two important deductions have been made from the Mitscherlich equation:—

(1) It has been used, as already stated, for estimating the amount of plant food present in a soil: this will be further discussed later (p. 525).

(2) The equation requires that, if two factors L and M vary simultaneously, each should produce its own effect independent of the other.

For if y, y' represent the yields when x, x' are the quantities of factor L, the quantity of factor M remaining constant, then

$$y = A(1 - e^{-cx})$$
$$y' = A(1 - e^{-cx'})$$

where A is the maximum yield obtainable with any quantity of factor L at the given value of M.

Now $$\frac{y}{y'} = \frac{1 - e^{-cx}}{1 - e^{-cx'}}.$$

[1] *J. Amer. Soc. Agron.*, 1932, **24**, 12, 610.

This ratio is therefore independent of the value of A, *i.e.* it is independent of the level at which M is taken.

Thus the ratio of the yields given by different quantities of a factor should remain the same no matter how much another factor may vary, for this will affect only A, the quantity that has been eliminated. Another way of expressing the result is this: if a certain change in one factor is made at different levels of a second factor the ratios of the yields should remain constant. This does sometimes happen. Table 30 shows the result of a pot experiment with oats

TABLE 30.—YIELD OF OATS IN POT EXPERIMENTS WITH VARIED PHOSPHATE DRESSINGS AND VARIED WATER.

(*Adapted from Mitscherlich.*)

Calcium Phosphate. (x).	Water 1 dose. (y).	Water 2 doses. (y').	Ratio. $\frac{y}{y'}$.
0	6·4	11·0	1·72
1	14·6	25·6	1·75
2	22·6	36·6	1·62
4	29·7	53·1	1·79
8	41·3	70·5	1·71
16	50·8	77·5	1·53
32	55·7	88·5	1·59

growing in sand receiving different quantities of phosphate and of water; the relative effect of the doses of water remained the same, no matter how much phosphate was given.

But Balmukand at Rothamsted has shown that it is not always so, and has developed another equation which appears to fit the facts better, based on Maskell's resistance formula.[1] He regards each activity of the plant (*e.g.* rate of growth, accumulation of dry matter) as being determined by a potential and a set of resistances, each of which represents one of the external factors. The effect of varying the quantities of any

[1] E. J. Maskell, 1925, thesis in Univ. of Cambridge Library; *Proc. Roy. Soc.*, 1928, B, **102**, 488; B. Balmukand, *J. Agric. Sci.*, 1928, **18**, 602.

one factor is most pronounced when the remaining "resistances" are relatively small, and less pronounced when they are great, but they all come into play continuously.

The relationship between the particular plant activity and the external factors is expressible by the general equation

$$\frac{1}{y} = F(A) + F'(B) + F''(C) + \ldots + K,$$

where y = the activity and A, B, C the factors. Maskell expresses the effect of nutrient supplies on total plant growth, *i.e.* yield :—

$$\frac{1}{y} = F(N) + F'(K) + F''(P) + \ldots + K,$$

y being the yield, F(N), F'(K), F''(P) being functions of the amounts of these nutrients supplied, and they have the form

$$\frac{a_n}{n + N'} \quad \frac{a_k}{k + K'} \quad \frac{a_p}{p + P'}$$

where N, K, P represent the amounts of these nutrients added ;

n, k, p represent the amounts in the seed and available in the soil ; a_n, a_k, a_p are constants expressing the importance of the nutrient to the crop, or its power to extract the nutrients from the soil : they are of the same numerical order as the minimum amounts of the nutrients in the crop grown under starvation conditions.

Maskell's expression, like Mitscherlich's, assumes that each factor acts independently of all the others.

Balmukand [1] has applied the equation to Gregory's pot experiments with barley at Rothamsted in which pairs of pots receiving equal quantities of phosphate differed only in nitrogen supply. According to the Mitscherlich equation the ratios of the yields of the different pairs should remain constant (p. 140) ; according to the Maskell equation the differences between the reciprocals of the yield should be constant : Table 31 shows that this is more nearly correct.

[1] *J. Agric. Sci.*, 1928, **18**, 602.

TABLE 31.—YIELDS OF BARLEY, DRY WEIGHT PER POT. F. G. GREGORY'S DATA USED BY BALMUKAND.

P_2O_5 mg. per Pot.	Mgms. N per Pot.		$\frac{y}{y'}$.	$\frac{1}{y} - \frac{1}{y'}$.
	15.	1215.		
5	3·06	15·00	4·902	·2602
15	3·36	17·88	5·321	·2417
45	3·03	29·60	9·769	·2963
135	2·39	68·10	20·089	·2784
405	3·60	86·40	24·000	·2663

From the Maskell equation, as from the Mitscherlich, it is possible to calculate a value representing the amount of the nutrient originally present in the soil, *i.e.* the amount of " available " nutrient: this is done by evaluating n, k, etc., and deducting the amount present in the original seed. The availability is, however, expressed in terms of the effect of added fertiliser rather than of absolute quantities in the soil.

(*b*) *Water Supply.*

This has proved very difficult to study quantitatively because the need for water is continuous, but the amount

TABLE 32.—INFLUENCE OF WATER SUPPLY ON THE EFFECTIVENESS OF MANURES. VON SEELHORST AND TUCKER (*J. f. Landw.*, 1898, **46**, 52).

(*Dry Weight of Oat Crop.*)

Manuring.	Nitrogen Series.			Increased Crop for	
	KP.	KPN.	KP, 2N.	First Increment of Nitrogen.	Second Increment of Nitrogen.
I. Moist soil	67·5	68·5	68·5	1·0	0
II. Moister soil	83·6	93·4	94·0	9·8	·6
III. Wettest soil	99·5	119·5	135·0	20·0	15·5

K = 1 grm. of K_2O as K_2CO_3 per pot; P = 1 grm. of P_2O_5 as $Ca(H_2PO_4)_2$ per pot; N = 5 grm. of N as $NaNO_3$ per pot.

Note.—The moist soil contained 14·35 per cent. of water (41·6 per cent. of saturation), the moister soil 15·41 per cent. at the beginning, increasing to 18·43 (51·7 per cent. of saturation) as the experiment proceeded, and the wettest soil, 16·44 per cent. at the beginning, increasing to 22·59 (63·7 per cent. of saturation).

required varies greatly with the conditions and according to the stage of growth of the plant. The close relation between water supply and effectiveness of nutrients was clearly established by C. von Seelhorst at Göttingen in pot experiments some forty years ago. Increases in nutrient supply had little effect in the rather dry soil, but an increasing effect as the water supply rose up to a certain point. Also the effect of the water increased as the nutrient supply was raised (see also p. 37).

This marked interaction of water and nutrient effects is well brought out in the field experiments on cotton carried out in the Gezira by F. G. Gregory and F. Crowther and A. R. Lambert—perhaps the best field experiments yet made on the subject. Only the first series need be quoted, the second was complicated by varying the spacing and sowing date but it gave similar results. Water was supplied at three rates, and sulphate of ammonia at two: the yields of seed cotton were, in kantars per feddan :—[1]

TABLE 33.—INFLUENCE OF WATER AND NITROGEN SUPPLY ON THE YIELD OF SEED COTTON.

	Rate of Watering.		
	Light.	Medium.	Heavy.
No added nitrogen . .	1·38	1·54	1·58
300 sulphate of ammonia .	1·98	2·45	2·80
600 „ „ „ .	2·28	3·04	3·79

Additional water was almost ineffective in absence of added nitrogen, but it greatly increased the yield when nitrogen was given, and it enhanced the effect of each level of nitrogen supply (Fig. 14).

This enhancement of effect of one factor by another is called an interaction, and in properly planned experiments it

[1] *Sudan Govt. Agric. Research Rept.*, 1928-1929, Physiol. Section, 95-117; *J. Agric. Sci.*, 1932, **22**, 617. See also F. Crowther, *Royal Agric. Soc. Egypt Tech. Bull.* No. 24, 1936.

1 kantar per feddan = 300 lb. per acre.

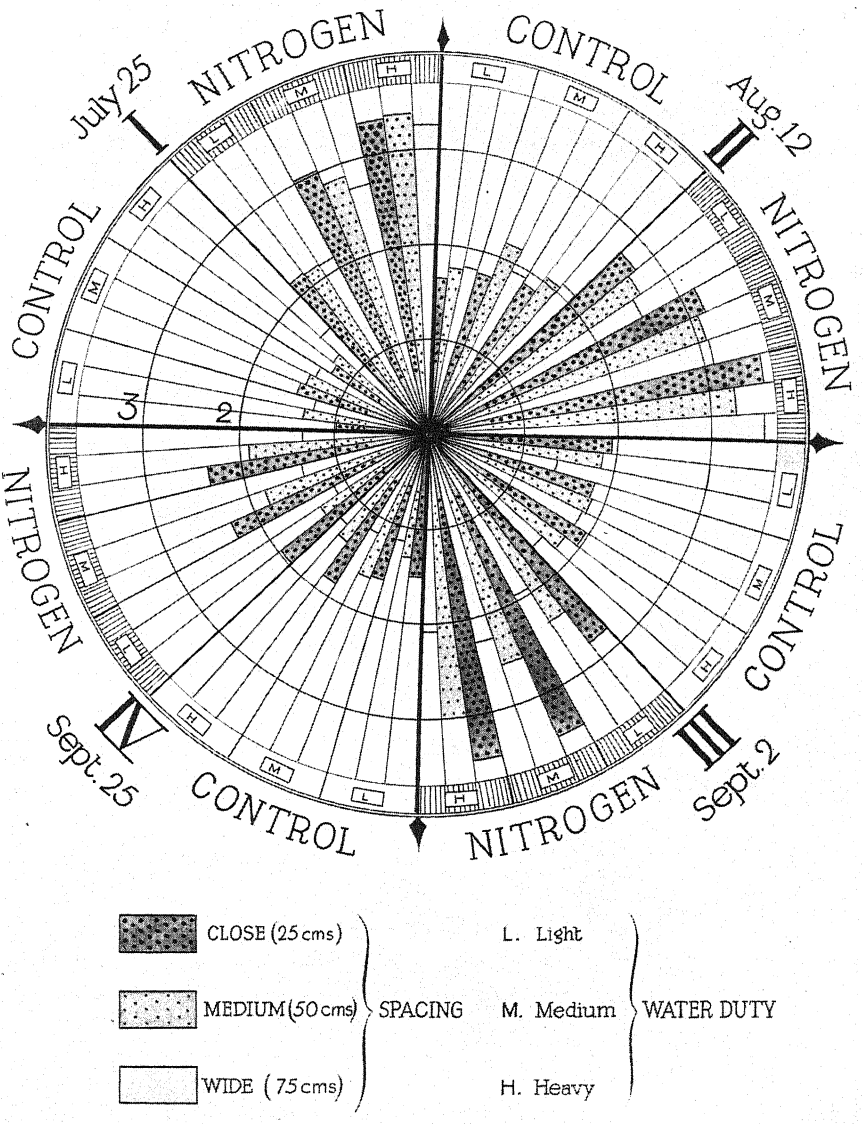


FIG. 14. Figure illustrating the interaction between water supply, nitrogen supply, spacing of plants (*i.e.* area of soil), and sowing date for cotton. Gezira Research Farm, Sudan, F. G. Gregory, F. Crowther, and A. R. Lambert. (*J. Agric. Sci.*, 1932, **22**, 627). *By courtesy of Camb. Univ. Press.*

can be studied in some detail.[1] The simplest presentation is afforded by F. F. Blackman's conception of " limiting factors " *i.e.* factors which by their insufficiency prevent other factors from increasing plant growth. This conception has proved very useful; in its general form it is shown in Fig. 15 which has often served as a first approximation in expressing

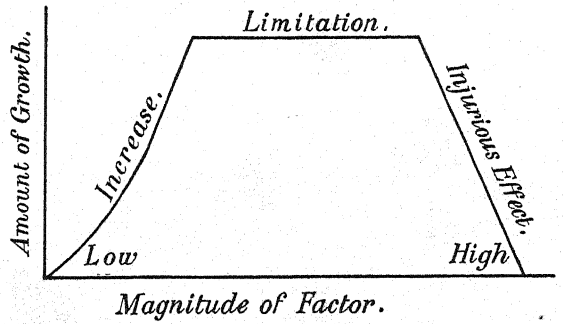


FIG. 15.—General relation between any particular factor and plant growth. An increment in the factor causes increases in growth up to the point when some second factor sets a limit; further increases then have no effect. Finally, excess of the factor brings into prominence any injurious effects it may exert.

experiment results although in practice the transition from one effect to another is not sharp as shown here but rounded off.

(*c*) *Temperature.*

The effect of temperature is still more difficult to deal with quantitatively. The separate processes in the life of the plant: respiration, assimilation, etc., increase with increasing temperature nearly up to the death point. But above a certain range of temperature the increased activity is not long

[1] Examples of positive interaction are found in the Rothamsted Annual Reports, *e.g.* 1934, p. 194, Beans: Nitrochalk and Muriate of Potash; p. 232, Potatoes: Potassic and phosphatic fertiliser. The interaction is negative when a fertiliser gives less increase in presence of another than when used alone: on p. 229 of the same Report sulphate of potash and farmyard manure both increased the yield of potatoes, but the potash was more effective when used alone than when given in addition to farmyard manure.

maintained; the protoplasm soon begins to suffer injury and the mechanism of the plant is thrown out of gear, so that the total growth does not increase and may even decrease at the higher temperature (p. 53 *et seq.*).

Field Conditions: Simultaneous Variation of Several Factors.

In field conditions the factors are so complex that the methods described in the preceding pages no longer suffice. R. A. Fisher at Rothamsted has developed methods of analysis whereby the relations between crop yield and meteorological or other measurable factors can be investigated, and the statistical significance of the relations can be tested. The statistical examination deals with effects and not with causes, but the resulting curves are invaluable for the examination of explanatory hypothesis.[1]

[1] R. A. Fisher, Studies in Crop Variation: I. "An Examination of the Yield of Dressed Grain from Broadbalk," *J. Agric. Sci.*, 1921, **11**, 107; "The Influence of Rainfall on the Yield of Wheat at Rothamsted," *Phil. Trans. Roy. Soc.*, Series B, 1924, **213**, 89; *Statistical Methods for Research Workers*, 5th Edition, Oliver & Boyd, Edinburgh, 1934.

CHAPTER III.

THE COMPOSITION OF THE SOIL.

THE soil was formed in the first instance from rocks partly by disintegration, partly by decomposition. In general the rock fragments were transported either by wind, water, or ice to some new situation where they have slowly undergone further changes. The most important of these are due to climatic factors and to the vegetation that springs up as soon as the surface is dry enough or stable enough to support it. Plants take from the soil nitrogen, phosphorus, potassium, calcium, and other elements which they return to the soil when they die. But they effect a far greater change. During life they have synthesised complex organic substances containing much stored up energy. After death these substances are added to the soil and so impart to the mineral matter stores of energy which they had not previously possessed. A vast population of micro-organisms then develops, living on this energy and food material, and effecting considerable changes in the soil.

The soil mass is in the main permeated with water, which dissolves some of its soluble constituents; and it is largely pervious to air. Thus the soil consists of four parts :—

(1) Mineral matter derived from the rocks, and subsequently more or less changed by leaching or by deposition of material from solution.

(2) Calcium carbonate and phosphate, and some resistant organic matter derived from marine or other organisms deposited with the rock particles during the sedimentary

stages of their existence. In arid regions notable quantities of soluble salts may be present.

(3) Residues of plants that have grown since the soil occupied its present position, containing organic matter synthesised by the plants, and nitrogen and mineral substances assimilated during their lifetime. These residues furnish food and energy for the soil population.

(4) The soil water, a dilute solution of carbonic acid, containing small quantities of every soil constituent.

The Mineral Matter Derived from Rocks.

The Insoluble Mineral Acids and their Salts.

While investigating methods of preventing loss of ammonia from manure heaps, H. S. Thompson (1850), a Yorkshire gentleman, found that soils have the power of absorbing ammonia from its solution. He communicated this result briefly to Thomas Way (1850), and they subsequently and independently discovered the even more surprising fact that, when sulphate of ammonia is mixed with soil, it cannot again be washed out with pure water, but calcium sulphate appears in its stead in the percolate. Way found that potassium salts behave similarly, and concluded that there exists in soil an active substance which, to quote his own words, "is really a *salt* of lime," arguing "that the retention of ammonia and potash by the soil could only be in the form of some insoluble salt of these alkalis, and could not have occurred without the existence of some similar salt of lime with which to interchange." This general idea is still held, but it is now usual to speak of the active substance as the "complex" and not as a salt. The interchange of bases is called "base exchange," the base so held in the soil being spoken of as "exchangeable" or "replaceable." The agents proposed by Way for the extraction of exchangeable bases, fairly strong salt solutions and dilute acids, are still those most generally used. In modern methods, common

solvents include 0·5*N* acetic acid, solutions of ammonium chloride or acetate or of sodium chloride. Special methods have to be adopted when calcium carbonate is present.

The results are generally stated as milligram equivalents of base per 100 grm. of dry soil. To avoid repetition of this awkward phrase, E. M. Crowther has proposed that the unit be called a "Way." The numbers of these units range from 5 or less in poor sandy soils to 15 in moderately poor heavy

TABLE 34.—PERCENTAGE COMPOSITION OF EXCHANGEABLE BASES FROM VARIOUS ACID OR NEUTRAL SOILS.

Soil.	100 Parts of Exchangeable Base contain :—							
	Chernozem, U.S.S.R., Gedroiz.	Podsol, U.S.S.R., Gedroiz.	Clay, Holland, Hissink.	Sandy humus, Holland, Hissink.	Various, Scotland, Smith.	Various, Calif., U.S.A., Kelley and Brown.	Rothamsted, England, Page and Williams.	Woburn, England, Crowther and Basu.
	(*a*)	(*a*)	(*b*)	(*b*)	(*c*)	(*d*)	(*e*)	(*f*)
Ca	82·1	80·5	79	76	88	63	92	79
Mg	15·1	13·4	13	13	7	25	5	13
K	2·7	6·1	2	3	2	4	3	3
Na	Nil	Nil	6	8	3	8	—	5
Total in mg. equiv. per 100 grms. soil[1] .	54·8	6·2	38·3	19·8	11·2	30·3	14·7	5·2

(*a*) K. K. Gedroiz (1927).

(*b*) D. J. Hissink, *Int. Mitt. Bodenk.*, 1922, **12**, 81. Average of twenty-five clay soils and of two sandy soils.

(*c*) Average of seventeen soils, A. M. Smith, *J. Agric. Sci.*, 1925, **15**, 466.

(*d*) Average of seven neutral soils, W. P. Kelley and S. M. Brown, *Calif. Agric. Expt. Sta.*, Tech. Paper No. 15, 1924.

(*e*) Broadbalk soil, Rothamsted, after continuous cropping with wheat without manure for eighty years, H. J. Page and W. Williams, *Trans. Faraday Soc.*, 1925, **20**, 573.

(*f*) Woburn soil, average of four plots after continuous cropping with wheat or barley without manure for fifty years, E. M. Crowther and J. K. Basu, *J. Agric. Sci.*, 1931, **21**, 689.

[1] *I.e.* the sum of the separate bases as determined.

soils, about 40 in more fertile heavy soils and 50 or more in prairie soils or chernozems. In neutral or nearly neutral conditions in temperate climates calcium commonly forms about 80 per cent. or more of these bases, magnesium about 10 to 15 per cent., the rest being chiefly sodium and potassium (Table 34). Iron and aluminium are also found in the dilute acid extracts of most soils, a fact that will be discussed in connection with soil acidity and exchangeable hydrogen (p. 156).

Liebig held that the absorption of ammonia and other bases by the soil was a physical process. This was long considered to be incompatible with Way's chemical hypothesis, but the two views are reconciled in the modern conception of salts as electrically charged atoms or atom-groups held together primarily by the physical force of electrostatic attraction. The electric components of a simple salt, the ions, dissociate from one another on dissolving in water and migrate when an electric current is passed through the solution. The positive ions move with the current (*i.e.* downstream) and so are called cations, while the negative ions, the anions, move against it. The soil complex, however, differs from a simple salt in that only the positively charged components are ions in the strict sense of the word : the negative charges are situated on particles so large, that under ordinary soil conditions they cannot dissolve but remain entangled with the rest of the solid matter.[1] When soil is stirred up with water the complex does not dissolve but the cations dissociate, and under the influence of an electric current migrate and can be separated from the anions by means of a cell just as in ordinary electrolysis, leaving an acid residue in the anode chamber. This process, under the name of electrodialysis, is used as an alternative method for the separation of exchangeable bases. It has also been used to render soils

[1] Under certain conditions they can be separated by cataphoresis as a suspension. A. Reifenberg, *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, 1, 38.

and their constituents completely "unsaturated," *i.e.* free from exchangeable base, though the product is liable to contamination by decomposition products.

During the passage of an electric current through wet soil water is carried forward with the cations; this process is called electrical endosmosis. A number of practical applications of this property have been made; *e.g.* if a ploughshare in passing through the soil is maintained at a negative potential a film of water is deposited on it and acts as a lubricant thereby reducing the draught of the plough.[1]

Clay Structure and Base Exchange.

A simple and fruitful conception of clay structure, adequate for a discussion of many base exchange phenomena in soils and clays, was put forward by Duclaux and used by Wiegner.[2] The large acidoid part, called the micelle, is pictured as a combination of alumina, silica, and iron hydroxides forming a complex alumino-silicic acid. This micelle carries a negative charge and is neutralised by a number of exchangeable ions.

The ordinary base exchange process is pictured simply as follows :—

$$\left[\begin{array}{c}\text{Clay}\\ \text{Micelle}\end{array}\right]\begin{array}{c}\text{Ca}\\ \text{K}\end{array} + 3\ \text{NaCl} \rightarrow \left[\begin{array}{c}\text{Clay}\\ \text{Micelle}\end{array}\right]\begin{array}{c}\text{Na}\\ \text{Na}\\ \text{Na}\end{array} + \text{CaCl}_2 + \text{KCl}.$$

All cations are not equally easily exchanged. Gedroiz (1918) using a chernozem saturated with either Mg, Ca or Ba as exchangeable ions, determined the power of certain chlorides to replace these cations (Table 35).

[1] E. M. Crowther and W. B. Haines, *J. Agric. Sci.*, 1924, **14**, 221.

[2] Wiegner summarised his views in *J. Soc. Chem. Ind.*, 1931, **50**, 55T, 65T, and 103T, and finally in his address to the International Society of Soil Science at Oxford, 1935 (*Trans. 3rd Int. Cong. Soil Sci.*, **3**, 5). This was his last important discourse : on receiving the reprints he said, "Siehst du, in *dem* Vortrag steckt meine ganze Lebensarbeit auf bodenkundlichem Gebiet."

TABLE 35.—REPLACING POWER OF DIFFERENT CATIONS. MILLI-EQUIVALENTS OF Mg, Ca, OR Ba, DISPLACED PER 100 GRM. OF SOIL BY ALKALI CATIONS ADDED AS CHLORIDES.

Chernozem.	Mg.	Ca.	Ba.
Conc. of chloride . . .	0·1*N*	0·01*N*	0·1*N*
Chloride added :—			
Li	—	1·4	7·6
Na	13·9	1·8	9·1
K	20·4	5·0	13·5
Rb	—	5·7	15·5
NH_4	20·4	5·7	12·9
Mg	—	5·3	15·4
Ca	35·2	—	20·4

The replacing power of the alkali metals from solutions of their chlorides increased as their atomic weight increased, *i.e.* in the order Li, Na, K, Rb ; the replacing power of Mg was similar to that of Rb, while that of Ca was still stronger. Ammonium, though not a metal, behaved very like K. These results have been repeatedly confirmed and little has been added by later workers. At much higher concentrations of the added chloride, however, the replacing powers of all these ions, with the possible exception of Na and Li, appear to be about the same.[1] Gedroiz's results further show that the Mg is more easily replaced from magnesium chernozem than is the Ba from barium chernozem. Little additional evidence has been obtained on this point though analogy with permutite suggests that the ease of replacement of exchangeable cations from homionic soils, *i.e.* soils containing only one kind of exchangeable base, decreases as the atomic weight increases, *i.e.*, it decreases in the order Li, Na, K, Rb, Cs and Mg, Ca, Ba. Thus the greater the power of a given base to displace other bases from a soil, the more firmly is this base held by the soil. This last result does not, however, apply to the complete removal of any particular

[1] G. Wiegner, *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **3**, 5 ; also N. C. Cernescu, *Anu. Inst. Geol. Român.*, 1931, **16**.

base from a soil and Mg may be the most difficult, K the next and Na and Ca the easiest bases to remove completely.

Base exchange reactions are not always reversible. Potassium chloride reacting with a sodium clay does not give the same absorption product as sodium chloride reacting with a potassium clay even when the micelle is the same and the ratio of potassium to sodium chlorides at the final equilibrium is the same also.[1] The reaction :—

$$\boxed{\text{Clay}}\begin{matrix}\text{Na}\\\text{Na}\end{matrix} + 2\text{KCl} \rightarrow \boxed{\text{Clay}}\begin{matrix}\text{K}\\\text{Na}\end{matrix} + \text{NaCl} + \text{KCl}$$

does not give the same clay product as :—

$$\boxed{\text{Clay}}\begin{matrix}\text{K}\\\text{K}\end{matrix} + 2\text{NaCl} \rightarrow \boxed{\text{Clay}}\begin{matrix}\text{K}\\\text{Na}\end{matrix} + \text{NaCl} + \text{KCl}$$

A similar result was obtained in the interaction of ammonium clay and calcium chloride as compared with that of calcium clay and ammonium chloride. On the other hand, the barium-calcium and barium-copper exchanges were completely reversible. The results were the same with a bentonite and a soil clay.

The exchange of cations is not only instantaneous, but the equilibrium is hardly affected by temperature. Up to the present no satisfactory mathematical formula has been devised to express the base exchange equilibrium, though many efforts have been made.[2]

Two interesting observations throw some light on the phenomena of base exchange. The exchange capacity is increased by " cleaning " the soil with a very weak solvent capable of removing precipitated hydroxides of iron, alumina, etc. ;[3] and it is decreased by precipitating alumina on the

[1] A. P. Vanselow, *Soil Sci.*, 1932, **33**, 95.

[2] See H. Jenny, *Kolloid-Beih.*, 1926, **23**, 428 ; A. P. Vanselow, *Soil Sci.*, 1932, **33**, 95 ; C. E. Marshall and R. S. Gupta, *J. Soc. Chem. Ind.*, 1933, **52**, 433T ; N. I. Gorbunov, *Proc. Gedroiz Inst. Soil Sci. and Fert.*, Moscow, 1933, **2**, 51 ; J. F. Fudge, *Soil Sci.*, 1935, **40**, 269 ; H. Jenny, *J. Phys. Chem.*, 1936, **40**, 501.

[3] M. Drosdoff, *Soil Sci.*, 1935, **39**, 463.

clay.[1] The base exchange capacity of a soil is closely related to various other properties, *e.g.* the heat of wetting and the absorption of vapours.

The Insoluble Soil Acids.

Removal of cations frequently occurs in natural conditions leaving the so-called "sour" or acid soils. It has long been known that they are acid to litmus paper but become neutral on addition of lime or calcium carbonate. The older chemists took the simple view that the acidity was due to an organic acid which they assumed to be identical with that present in peat. Its formation was attributed to restricted decomposition of the plant residues due to badly aerated undrained conditions, but no one ever succeeded in extracting it from the soil.

Moreover, subsequent observations showed that some acid soils were well drained, well aerated, and poor in organic matter. As in the case of base exchange, a controversy arose between those who viewed the phenomena as mainly physical, the result of a preferential or selective absorption, and those who considered that true chemical acids were present.

The development of the hydrogen electrode enabled the hydrogen ion concentrations in soil suspensions to be determined, and greatly stimulated investigation: this was further facilitated by the adoption of the *p*H notation. Soils behave like weak polybasic acids in that their reaction changes slowly and continuously with successive additions of acid or alkali. There is no steady period followed by a sudden change at the end as happens in titration of a strong acid or alkali; instead of requiring the addition of a mere trace of acid to bring the suspension to *p*H 4 (enough to make it 0·0001*N* acid) and a mere trace of alkali to take it to *p*H 10 (enough to make it 0·0001*N* alkaline) soils require considerably more. This hampering of the titration is called buffer action and the

[1] H. Paver and C. E. Marshall, *Chem. and Ind.*, 1934, **12**, 750. The significance of this precipitation is here discussed.

curve showing the reaction plotted against the quantity of acid or alkali added is called a buffer or titration curve.

The most direct way to obtain these curves is to add increasing small doses of strong acid and alkali to a series of soil suspensions in water and after allowing sufficient time for the attainment of equilibrium to measure the *p*H by one of the recognised methods. The *p*H is then plotted against the amount of alkali added (positive values) and the amount of acid added (negative values). Measurements of this kind were first made by L. T. Sharp and D. R. Hoagland [1] on soil and by R. Bradfield [2] on electrodialysed clay and have since been carried out by many others. An indirect

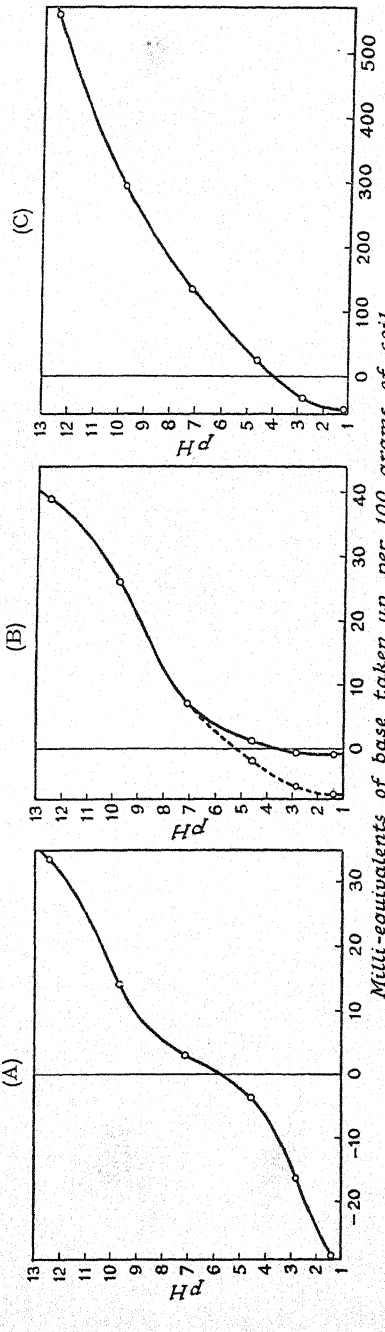


FIG. 16.—Buffer curves of three dissimilar soils (R. K. Schofield): (A) English subsoil; (B) South African subsoil; (C) a peat.

[1] *J. Agric. Res.*, 1916, **7**, 123.

[2] *J. Amer. Chem. Soc.*, 1923, **45**, 2669.

but more accurate method has recently been worked out by R. K. Schofield[1] in which the soil samples are placed in a series of solutions strongly buffered at different *p*H values and titrated. The difference from the original titre of the solution shows the amount of base given to or taken from the soil by the solution. The buffer curve can thus be plotted, the *p*H for each point being that of the solution used, the values for base absorbed by the soil being plotted as positive and for base given up from the soil as negative. Curves for an English subsoil, a South African subsoil and a peat are shown in Fig. 16. The first shows two separate *p*H ranges, about *p*H 3 and *p*H 10 respectively, in which the *p*H alters but little with change in base content: *i.e.* in which the buffering is strongest. In the second curve there is a single maximum round about *p*H 9, while the peat curve shows a steady increase in buffering with rise in *p*H.

For weak monobasic acids like acetic the form of the buffer curve is almost independent of the base used and is not seriously affected by the addition of salts like alkali or alkaline earth chlorides. Polybasic acids like phosphoric acid, however, behave differently, as also do soils. The negative components of the "complex" are multicharged particles showing even more markedly the behaviour of polybasic acids, and there is a distinct fall in *p*H when a salt like potassium chloride is added to a suspension of soil in water. The potassium ions, replacing hydrogen from the exchange complex, cause an increase in the hydrogen ion concentration of the liquid.

Soil acidity is closely connected with the aluminium. This is illustrated in Fig. 17. The heavy full curve on the left is for an unmanured plot in the Rothamsted Park Grass, that on the right is for a neighbouring plot which has received eighty annual dressings of 600 lb. sulphate of ammonia per acre. After treatment with aluminium chloride the unmanured soil gave the dotted curve, and its resemblance to the curve for the sulphate of ammonia plot provides striking

[1] *Trans. VI. Comm. Int. Soc. Soil Sci.*, Groningen, B, 1933, p. 80

support to H. Paver and C. E. Marshall's [1] view that in acid soils alumina acts as an exchangeable base. On the other hand, soil from the sulphate of ammonia plot treated first with dilute hydrochloric acid and then with a gentle stream of hard water for several days gave curve No. 1 which is so like that for the unmanured soil as to suggest that calcium had displaced the aluminium ions making once more a "salt of lime." The aluminium liberated when acid soils are leached

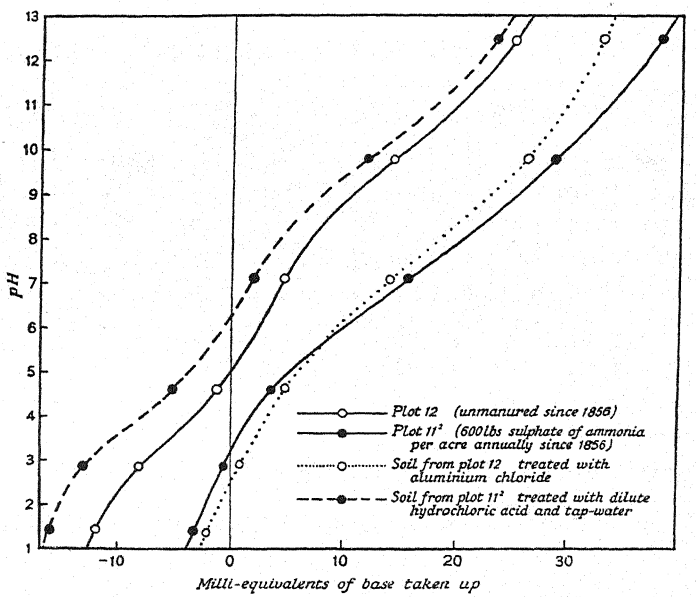


FIG. 17.—Influence of aluminium on the buffer curve of Rothamsted soil (R. K. Schofield).

with neutral salt solutions contributes largely to the so-called "exchange acidity" determined by titrating the leachate to a neutral or alkaline end-point. There may also, however, be a direct exchange between the cations of the salt and hydrogen ions from the soil acid.

Many attempts have been made to measure the amount of "exchangeable hydrogen" in the soil. The buffer curve

[1] *Chem. and Ind.*, 1934, **12**, 750.

shows how much base must be added (and therefore how much hydrogen must be exchanged) in order that the suspension may have a given *p*H. Since this continues to increase up to the highest *p*H that can be used without causing serious decomposition we are left in doubt as to whether there is a true limit to the amount of exchangeable hydrogen. For the same reason "base exchange capacity," *i.e.* the capacity of a soil to hold exchangeable bases, is defined only when the *p*H is specified and, to be strict, the concentrations and nature of the bases and salts in the suspension. Many apparent anomalies were recorded in the literature before the importance of controlling the *p*H was recognised.

Amphoteric Behaviour.—When either the English subsoil of Fig. 16 or the peat is placed in dilute hydrochloric acid the chloride concentration of the solution is not appreciably affected, but bases leave the soil and convert some of the acid into alkali and alkaline earth chlorides. The South African subsoil, however, yields up very little base but actually absorbs an appreciable quantity of the acid. There is considerable evidence that in acid solutions some soil constituents can lose hydroxyl ions and so become positively charged and retain the anions as electrical partners; the hydroxyl ions meanwhile reacting with the hydrogen ions of the solution. Mattson, indeed, considers that the active components of soil are commonly amphoteric, *i.e.* they dissociate hydroxyl ions on the acid side of an isoelectric *p*H (the point at which the particles carry no electric charge), and hydrogen ions on the alkaline side; this isoelectric *p*H being largely determined by the conditions of weathering and being different in succeeding horizons of a mature soil profile. The idea is suggestive but it is not yet established.

There is evidence that anions like phosphate can by virtue of some secondary valency attach themselves to negatively charged soil particles, *i.e.* against electrostatic repulsion, the attachment being therefore no proof of amphoteric behaviour. Until it is better understood this kind of binding cannot be

distinguished with certainty from that due to the electrostatic attraction of a positively charged particle.

Even in the case of cations the bond may not be solely electrostatic; some further mode of union is suggested by the well-known power of aluminium ions to reverse the direction of the endosmotic stream, more of them apparently being attached to the surface of the complex than are needed to balance the changes in the buffer curve caused by leaching with aluminium chloride. The state of knowledge of physical chemistry is the chief factor limiting the understanding of these phenomena.

The Soil Components: Inorganic or Mineral Substances.

Separation and Identification.

A. Physical or Mechanical Methods: Separation According to Grain Size.

Mere inspection of soil shows that it is composed of particles of different sizes possessing a greater or less tendency to stick together and form larger aggregates. These can be put into three groups, though the separation is not sharp or exact; clods, which are large and can be broken down by gentle mechanical means; crumbs and granules, which are smaller, but in which the particles are more tenaciously held, so that some gentle chemical treatment is necessary to separate them; and concretions in which the fine material is bound still more firmly by a cement containing inorganic colloids. The power of forming clods and crumbs resides partly in the organic matter and partly in the mineral particles of smallest size, of which a relatively small percentage suffices.

The first step in separating a soil into its component particles is therefore to overcome this cementing action, and

this is done by grinding or crushing the aggregates until all the fine material has passed a 2 mm. sieve. This process, however, introduces an arbitrary element into the mechanical analysis of some types of soil. The concretions are usually very hard, and remain intact during mechanical analysis, but in some tropical and subtropical soils they are soft enough to be more or less broken down by the preliminary grinding.

The second process consists in dispersing the fine aggregates; this is usually performed by oxidising the organic matter, removing calcium salts such as carbonate and sulphate, and adding a dispersing agent which prevents the particles from sticking together. For many soils dispersing agents can be found that render the first two steps unnecessary: naturally they must be sufficiently gentle in action to avoid the destruction of any appreciable proportion of the soil material. All methods are conventional and differ slightly in their results, especially for calcareous soils containing large amounts of calcium carbonate or peat and fen soils containing 20 per cent. or more of organic matter. For soils containing but little calcium carbonate, or organic matter the present International method gives satisfactory results: it consists in oxidising the organic matter with hydrogen peroxide, treating with dilute hydrochloric acid and dispersing the finest particles with a dilute solution of ammonia or sodium hydroxide.

The particles thus disaggregated are separated into groups lying between certain conventional limits of size. The upper limit 0·002 mm. diameter was chosen for the clay fraction because this approximately marks the region where colloidal properties begin to show clearly. Above this limit they hardly appear; below it they show with rapidly increasing intensity as the particles become smaller.

Some method of specifying the size of the particles must be adopted. Microscopic examination shows that the particles have no simple geometrical shape; some may form

thin flakes, and others are more or less spherical or cubic, but most of them are very irregular and no simple measurement can adequately express their size. The mass and the volume are definable for the larger particles but not for the fine colloidal particles; if, however, either of these could be determined experimentally it would afford an adequate measure of the size of the particles present. But there are no methods yet available for determining either mass or volume distribution of the particles. Two indirect determinations are therefore used. The size-limits of the larger particles are defined by certain standard sieves. For the finer particles the property measured is their velocity of sedimentation in a vertical column of water at a certain standard temperature, usually 20° C. The result is usually expressed, not as the experimentally determined settling velocity, but as the diameter of a sphere of density 2·55 that would, according to Stokes' law, have the same settling velocity. The fact that many of the particles do not happen to possess this density is no more disturbing than the fact that they are not spherical.

Finally, convenient limits are selected for separating the particles of different conventional size. The four size groups now usually adopted for dividing the "fine earth," which passes the 2 mm. sieve, are coarse sand, fine sand, silt and clay; on the present international system the upper size limit of each of the first three fractions is ten times the lower size limit. The coarse sand is separated on a sieve and the other three groups by their different sedimentation velocities (Table 36). The actual separation may be made by settling and decantation, or, much more rapidly, by taking samples with a pipette from a standard depth after standing for definite periods.

Separation by elutriation is much in favour on the Continent as an alternative method for the finer fractionation of the sand fractions. The soil is fractionated by means of an upward current of water, the velocity of flow being adjusted

TABLE 36.—NAMES AND SIZES OF FRACTIONS OBTAINED BY MECHANICAL ANALYSIS OF SOILS IN DIFFERENT COUNTRIES.

Older British (replaced 1928).		American[1] (Bureau of Soils).		Older German Work[2] (Verband. Landw. Vers.-Sta.).		International (based on Atterberg).[3]	
Name of Fraction.	Limits of Diameter of Particles, mm.	Name of Fraction.	Limits of Diameter of Particles, mm.	Name of Fraction.	Limits of Diameter of Particles, mm.	Name of Fraction.	Limits of Diameter of Particles, mm.
Fine gravel	3-1	Fine gravel	2-1	Steine	above 5	Gravel (Kies)	above 2
				Grand	5-2		
				Sehr Grober sand	2-1		
Coarse sand	1-0·2	Coarse sand	1-0·5	Grober sand	1-0·5	Coarse sand	2·0-0·2
		Medium sand	0·5-0·25	Mittelkörniger sand	0·5-0·2		
Fine sand	0·2-0·04	Fine sand	0·25-0·10	Feiner sand		Fine sand (Mo, Feinsand)	0·2-0·02
		Very fine sand	0·10-0·05	Sehr feiner sand	below 0·2		
Silt	0·04-0·01	Silt	0·05-0·005	Mineralstaub		Silt (Schluff, Staub)	0·02-0·002
Fine silt	0·01-0·002			Ton			
Clay	below 0·002 [4]	Clay	below 0·005			Clay (Ton, Schlamm)	below 0·002
		Colloidal fraction	below 0·002				

[1] L. B. Olmstead, L. T. Alexander, H. E. Middleton, *U.S. Dept. Agric. Tech. Bull.* No. 170, 1930. Except the "Colloidal fraction" the old grouping of Whitney is retained.

[2] *Landw. Vers.-Sta.*, 1894, **43**, 335. The first five fractions are separated by sieves, and the others in Kühn's sedimenting cylinder. Ramann adopted the American limits, but divided the clay into *Feiner Staub*, 005-·0015 mm., and *Schlamm*, below ·0015 mm.

[3] *Int. Mitt. Bodenkunde*, 1912, **2**, 312. The international method is described in Tech. Com., No. 26, *Imp. Bureau Soil Sci.*, Rothamsted, 1933.

[4] Probably smaller: the calculated value for the upper limit is 0·0014.

so as to balance exactly the corresponding sedimentation velocities.[1]

Fuller information about the size distribution of soil particles is given by distribution curves, obtained by dividing the soil particles not into five but into a large or even infinite number of groups according to their settling velocities, and plotting the results by some suitable method.

The first curves of this type were obtained by Odén (1915). He used an automatic balance to record the weights of the sediments at any time, and discussed the results in a brilliant series of papers described in Keen's monograph (1931). Unfortunately the difficulties caused by convection currents have not been overcome, though they can be minimised.[2] Wiegner devised an alternative but less precise method, based on measurements of the changes in the hydrostatic pressure of a column of suspension consequent on the deposition of the solid matter,[3] while E. G. Richardson [4] and others have described optical methods of estimating the amounts of suspended matter still left at any given moment, and so obtaining a record of the rate of settlement.

Robinson [5] constructed his curves by plotting the weight of the fraction per 100 grms. of soil having a settling velocity less than v against the logarithm of this settling velocity. The experimental procedure is very simple, necessitating only sampling by means of a pipette. All the soils examined gave smooth curves.

The further sub-division of the clay fraction has been

[1] For an account of these methods see H. Gessner, *Die Schlämmanalyse*, Leipzig, 1931. For Bouyoucos' hydrometer method see *Soil Sci.*, 1928, **26**, 233.

[2] C. W. Correns and W. Schott, *Kolloid Ztschr.*, 1932, **61**, 68. These authors found that with proper precautions in preparing the sample, the methods of Odén, Atterberg, and Robinson all gave similar curves.

[3] For a detailed description of this and many other methods see H. Gessner, *Die Schlämmanalyse*, Leipzig, 1931.

[4] *J. Agric. Sci.*, 1934, **24**, 457, and *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 40.

[5] *J. Agric. Sci.*, 1922, **12**, 306, and 1924, **14**, 626.

greatly facilitated by the improved methods of separation in centrifuges. Distribution curves of settling velocities can now be obtained for particles having an equivalent diameter down to 50 mμ.

TABLE 37.—THE DISTRIBUTION OF PARTICLE SIZES IN FOUR CLAY TYPES [1] (CONVERTED INTO SODIUM CLAYS).

Clay.	Concentration, per cent.	2μ–1μ.	1μ–0·5μ.	500–200 mμ.	200–100 mμ.	100–50 mμ.	50 mμ.
Rothamsted	0·5	15·2	12·1	18·7	14·3	10·3	29·4
Putnam .	0·5	7·8	6·6	11·8	11·6	21·3	40·9
Bentonite .	0·5	15·1	18·7	20·9	10·1	7·9	27·3
Kaolin .	0·2	65·2	20·8	6·5	7·5	—	—

B. CHEMICAL METHODS FOR INVESTIGATING THE SOIL MINERALS.

Way, in 1852, concluded that the substance concerned with the exchangeable bases in a soil was "a salt of lime," and he tried to discover its properties. He showed it was in the clay, and, moreover, it lost its power on ignition. No known simple silicates possessed these properties, but he prepared a number of "double silicates" of lime and alumina, etc., that did; thus they reacted, like clay, with ammonium salts to form an almost insoluble double ammonium silicate and a soluble calcium salt, and also, like clay, they lost this property after ignition. Although he did not establish the existence of such double silicates in the soil, their resemblance to the reactive constituent in the soil was so close that he considered himself justified in assuming their presence.

Since that time many investigators have searched for the active constituent. The existence of Way's assumed "double silicates" was never established, but after the discovery that the properties attributed to them were actually possessed by the zeolites, a group of crystalline alumino-silicates found in cavities in igneous rocks or formed in the decomposition of

[1] C. E. Marshall, *J. Soc. Chem. Ind.*, 1931, **50**, 457T.

felspars, it was assumed that zeolites must be present in the soil, and therefore must be the reactive bodies concerned. But zeolites were never shown to occur in the soil, and the whole supposition became unnecessary after Lemberg's discovery that many other silicate minerals besides zeolites are reactive, and exchange bases in salt solutions.[1]

Van Bemmelen (1877, 1904) studied the soil silicates in detail, and showed that they could be divided into two groups :—

(1) The unweathered portion which occurs as crystals even in clay, and to which chemical formulæ can be assigned ;

(2) The weathered portion, which he considered to be an absorption complex of the form $SiO_2 . p\ Al_2O_3 . q\ Fe_2O_3 . r\ CaO$, etc., and not definite minerals or compounds to which chemical formulæ could be assigned. He divided these up into two classes :—

(*a*) Those completely decomposed by boiling hydrochloric acid, now often called Silicate A ;

(*b*) Those resistant to this treatment but decomposed by hot concentrated sulphuric acid, now often called Silicate B.

He established the fact that the bases held in Silicate B are, on the whole, not exchangeable and that Silicate A displays colloidal properties in a more marked degree than Silicate B.

He emphasised the important part played by the weathered silicates—the " amorphous zeolitic silicates which arise by weathering " to use his own words—in determining certain properties of the soil : they could be flocculated ; they dried to hard compact masses ; further, they absorbed various substances from solution and interacted by double decomposition with various salts. His analysis of the weathered silicate into the two substances A and B suggested that Silicate A was the reactive body causing the Way phenomena, and was also in part responsible for the colloidal properties of the soil.

[1] *Ztschr. Deut. Geol. Ges.*, 1870, **22**, 335 and 803 ; 1872, **24**, 187 ; 1876, **28**, 537 ; 1877, **29**, 483. For a summary of this important investigation see E. A. Fisher, *Trans. Faraday Soc.*, 1922, **17**, 305.

The method has been much used in Holland by Hissink, who has confirmed and extended van Bemmelen's view that Silicate A is the chief constituent possessing base exchange capacity. To quote only one example : in four Dutch soils, at least 90 per cent. of the base exchange capacity resided in the finest fraction, and about 70 per cent. of this was Silicate A :—[1]

Fraction : particle size .	16-43μ	8-16μ	2-8μ	Below 2μ
Silicate A present, per cent. . . .	4-25	7-14	14-20	70
Base exchange capacity per cent. of total .	0-5		4-7	>90

It is, however, recognised that the distinction is not sharp. Hydrochloric acid can decompose appreciable quantities of many parent rocks, *e.g.* basalts,[2] often some Silicate B, though not as vigorously as sulphuric acid,[3] and it does not decompose all the reactive material, *i.e.* material possessing base exchange capacity in the soil. The influence of the strength of the hydrochloric acid and of the temperature of digestion have been examined by van Bemmelen and many others. G. S. Fraps and J. F. Fudge [4] digested soils with hydrochloric acid of various strengths for a period of ten hours on a water bath, and found the loss [5] of exchange capacity as follows :—

Concentration of acid .	0·2	1·0	1·75	3·0	7·0	8·75N
Exchange capacity lost, per cent. . . .	17	47	64	74	80	80
Al_2O_3 extracted (calculated on amount dissolved by 8·75N HCl = 80) . . .	10	30	58	76	84	80

[1] For Dutch soils, Hissink gives the average molecular composition of Silicate A as Al_2O_3, 0·56 Fe_2O_3, 3·6 SiO_2, 12·9 H_2O. 25 per cent. HCl is used, and the extraction is completed with NaOH.

[2] W. Bujakowsky and C. Treschow, *Kgl. Veter.-og Landbohøjsk. Aarsskr.*, 1933, p. 121.

[3] R. H. J. Roborgh, "A Study of the Nature of Clay," *Thesis :* Wageningen, 1935.

[4] *J. Amer. Soc. Agron.*, 1935, **27**, 446.

[5] Average of twelve soils.

The quantities of alumina extracted showed some relation with the loss of exchange capacity, but the quantities of iron and silica did not. Roborgh showed that in successive extractions with HCl at 55°-75° C. the quantity of iron brought out rapidly decreased, but the SiO_2/Al_2O_3 ratio of the decomposed material and the base exchange capacity of the residual material remained nearly constant. Many other attempts have been made to distinguish between the products of recent weathering—usually assumed to be free oxides or hydroxides of silicon, iron, and aluminium—and the crystalline material, assumed to be either parent material or fairly old weathering products. The most widely used method is probably that of Tamm,[1] in which the soil is treated with acid ammonium or sodium oxalate. E. Truog has studied the separation of the soil constituents by chemical means, and with Drosdoff [2] has suggested separating free alumina and silica with hot sodium carbonate, while free iron hydroxide, which is more difficult to remove, is first converted into sulphide with H_2S and then into chloride.

But as with the hydrochloric acid used by van Bemmelen, the reagents are either not strong enough to dissolve out all the products of weathering or they also attack crystalline minerals at the same time. Indeed it is becoming clear that exact separation is impossible because there is no sharp separation of materials of the soil: one cannot say where the outer layers of weathered mineral on a crystal lattice end and where the unweathered lattice begins.

C. Mineralogical Analysis.

The standard mineralogical methods of analysis were applied to soils by Delage and Lagatu,[3] by the Dutch workers

[1] *Medd. Skogsförsöksanst.*, 1922, **19**, 385, and 1934, **27**, 1.

[2] *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 92. They also give methods for estimating the quantities and types of alumino-silicates in clay colloids (M. Drosdoff, *Soil Sci.*, 1935, **39**, 463).

[3] *Trav. École Nat. d'Agric.*, Montpellier, 1904, 1905, 1907.

van der Kolk [1] and J. van Baren,[2] by McCaughey and Fry [3] in the United States, and many others. Till recently these methods were applicable only to the sand and silt fractions; they could not deal with the finer material.

Since 1930, however, new methods have been introduced by means of which the clay fraction can be examined. C. E. Marshall uses an optical method for measuring the double refraction of clay particles in an alternating electric field,[4] and he also measures the distribution of refractive indices of clay particles and their mean density down to 50 mμ in diameter.[5]

A thermal method is used by V. Agafonoff and others [6] for the identification of the minerals in the clay fraction. It is based on Le Chatelier's observation that at a particular temperature many minerals undergo rapid decomposition with evolution or absorption of heat. These critical temperatures are characteristic of the particular mineral and are not much affected by the presence of other substances, so that by gradually raising the temperature of a clay in an oven, and recording by means of a thermocouple the curve showing sudden evolutions or absorptions of heat, a series of points is obtained from which the constituent minerals may be provisionally identified.

A second thermal method has been used by Kelley and his co-workers,[7] in which they determine the dehydration

[1] J. L. C. Schröder van der Kolk, *Tabellen zur mikroskopischen Bestimmung der Mineralien nach ihrem Brechungsindex :* Wiesbaden, 1906.

[2] *Mitt. Geol. Inst.*, Wageningen, 1928, No. 14. There is an admirable collection of soil minerals at the Geological Institute of the Agricultural University, Wageningen.

[3] W. J. McCaughey and W. H. Fry, *U.S.D.A. Bur. Soils*, Bull. No. 91, 1913. The methods are well described by W. H. Fry, *U.S.D.A. Tech. Bull.* No. 344, 1933.

[4] *Trans. Faraday Soc.*, 1930, **26**, 173.

[5] *Ztschr. Kryst.*, 1935, A, **90**, 8, and *Sci. Prog.*, 1936, **191**, 422.

[6] V. Agafonoff, *C.R.*, 1933, **197**, 166; 1935, **200**, 1058; *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1936, **3**, 74.

[7] W. P. Kelley, H. Jenny, and S. M. Brown, *Soil Sci.*, 1936, **41**, 259.

curves of the soil minerals and colloids. These curves give the amount of water lost at each stage as the temperature is slowly raised.

S. B. Henricks and W. H. Fry,[1] and also W. P. Kelley, W. H. Dore, and S. M. Brown [2] examined different minerals and soil colloids by X-ray diffraction methods. Unfortunately the crystals are too small to use separately, and only powder photographs have so far been obtained; as these are almost unaffected by certain important types of variation in the crystal lattice, the interpretation of the photographs and the identification of the minerals are both difficult.

The Principal Minerals found in the Soil.

I. Silt and Sand Fractions.

The minerals most commonly found in the silt and sand fractions, *i.e.* the non-colloidal fractions, of the soil are :—[3]

I. Quartz.

II. Felspars.

(*a*) orthoclase, a potash felspar ($KAlSi_3O_8$) [4];

(*b*) plagioclase, a series of mixed crystals having albite or soda felspar ($NaAlSi_3O_8$) and anorthite or calcium felspar ($CaAl_2Si_2O_8$) as end members. This group is not so resistant to weathering as orthoclase.

III. Pyroxenes and Amphiboles, a complex group containing typically magnesium calcium iron silicates, not very resistant to decomposition.

IV. Micas.

(*a*) containing no divalent metals;
muscovite, a potassium aluminium silicate which is fairly stable ($H_2KAl_3(SiO_4)_3$).

[1] *Soil Sci.*, 1930, **29**, 457. [2] *Ibid.*, 1931, **31**, 23.

[3] For details see H. B. Milner, *Sedimentary Petrography*, Murby & Co., 3rd edition, 1936; A. N. Winchell, *Elements of Optical Mineralogy*, John Wiley, 1933; P. G. H. Boswell, *Mineralogy of Sedimentary Rocks*, 1933; this has a good bibliography of soil papers.

[4] These formulæ are given only to show the type.

(*b*) containing divalent metals ;
biotite, a potassium magnesium iron aluminium silicate not very resistant to decomposition.
No calcium micas are known and soda mica is very rare.

(*c*) glauconite ; [1] a potassium iron silicate closely related to mica.

V. Various minerals such as apatite, zircon, garnet, hæmatite, limonite, magnetite, and ilmenite ($FeTiO_3$).

Of all these, quartz is by far the commonest in soil, usually accounting for 60 to over 90 per cent. of the sand fraction (Table 38) even in clay soils.[2] Thus Marshall [3] found in the Rothamsted clay soil (fraction 0·2-0·02 mm.) no less than 75 per cent. of quartz with 5 per cent. of orthoclase, 8 to 10 per cent. of coloured minerals (blue-grey tourmaline, etc.), and in addition zircon, micas, and chloritic material. The palæozoic soils of North Wales [4] and Scotland, however,[5] contain more undecomposed mineral silicate, as also do the granite soils of the South of France (Delage and Lagatu (p. 167), and soils in the arid parts of the United States (Table 38).

[1] J. W. Gruner, *Amer. Mineral.*, 1935, **20.**

[2] This is in marked contrast with the average content in the parent rock material which according to F. W. Clark is :—

	Per Cent.
Felspars	60
Amphiboles and Pyroxene	17
Quartz	12
Micas	4
Other minerals	7
	100

(analyses of 700 igneous rocks).

He further estimates that the lithosphere is composed of 95 per cent. igneous rocks and 5 per cent. sediments down to a depth of half a mile. (*U.S. Geol. Surv. Bull.* No. 770, 1924.)

[3] *Ztschr. Kryst.*, 1935, A, **90,** 8.

[4] G. W. Robinson, *J. Agric. Sci.*, 1917, **8,** 338.

[5] Hendrick and Ogg, *ibid.*, 1916, **7,** 458 ; 1920, **10,** 333.

TABLE 38.—PERCENTAGE OF QUARTZ AND OF OTHER MINERALS IN SAND AND SILT FRACTIONS SEPARATED FROM THE UNITED STATES SOILS. W. J. MCCAUGHEY AND W. H. FRY.[1]

Method of Formation.	Soil Type.	Sand Fractions.		Silt Fractions.	
		Percentage of		Percentage of	
		Minerals other than Quartz.	Quartz.	Minerals other than Quartz.	Quartz.
Chiefly disintegration .	Arid	37	62	42	58
Intermediate	Residual, Glacial and loessial	15	85	21	79
		12	88	15	85
Chiefly decomposition	Marine	5	95	8	92

The silt fraction (0·02-0·002 mm.), however, contains less quartz than the coarser fractions.

2. THE CLAY FRACTION.

(Particles below 0·002 mm. diameter.)

A change in composition rapidly sets in as the particles become finer. The original rock minerals almost disappear. They are very resistant and almost inert so long as they remain in relatively large particles, but they either dissolve or decompose readily when the particles become smaller. New minerals appear, formed apparently as decomposition products; they persist because they are more stable under the soil conditions. They are also more reactive and in presence of dissolved salts some of them have a marked power of base exchange, which becomes more pronounced in the finer fractions. Marshall obtained the following results on the Rothamsted clay :—[2]

[1] *U.S.D.A. Bur. Soils*, Bull. 91, 1913. See also W. O. Robinson, *U.S.D.A.*, Bull. 122, 1914, where there is a long list of soil minerals.

[2] *Ztschr. Kryst.*, 1935, **90**, 8.

	0·005–0·002 mm.	Below 0·002 mm.				
Size of fraction	5-2μ	2-1μ	1-0·5μ	0·5-0·2μ	0·2-0·1μ	Below 0·1μ
Quartz per cent. . .	20	20	<10	—	—	—
Base exchange capacity (mg. equivalents per 100 gms. ignited clay)	4-6	15-19	29-36	35-45	41-53	62-79

So far the following minerals have been identified in the clay fractions :—

1. *Not confined to clay :—*

   Quartz, chiefly in the coarser part of the clay.

   Micas, including glauconite.

2. *Clay minerals, products of weathering :—*

   (1) The Kaolin group: Kaolinite ($Al_2O_3 . 2SiO_2 . 2H_2O$), Nacrite, Dickite,[1] and Halloysite ($Al_2O_3 . 2SiO_2 . 2\text{-}4\ H_2O$).

   These minerals have only low base exchange capacity, usually less than 10 milli-equivalents per 100 grms. under natural conditions,[2] though Kelley and Jenny have been able to raise it tenfold by grinding in a ball mill. Under natural conditions kaolinite is not very finely dispersed, few particles being smaller than 0·1μ while halloysite occurs as finer particles. The members of this group have similar X-ray powder diagrams.[3]

   (2) Montmorillonite, $Al_2O_3, 4SiO_2$, but sometimes 3 or $5SiO_2$, about $5H_2O$, some calcium and magnesium but no iron ; this occurs in bentonite [4] and in fuller's earth.

[1] C. S. Ross and P. F. Kerr, *U.S. Geol. Surv.*, Prof. Paper No. 165E, 1931, and 185G, 1934.

[2] C. E. Marshall, *Ztschr. Kryst.*, 1935, **91**, 433. Edelman, however, asserts that halloysite has higher base exchange capacity.

[3] For a discussion of the properties of this group see S. R. Hind, *Trans. Ceramic Soc.*, 1927, 1928, **27**, 5 ; see also C. S. Ross, *Proc. 1st Int. Cong. Soil Sci.*, Washington, 1928, **4**, 555 ; *U.S. Geol. Surv.*, Prof. Paper No. 165E, 1931.

[4] The ease with which bentonite can be obtained, and its well-marked colloidal and base exchange properties, have made it a favourite material

Nontronite, Fe_2O_3, 3 or more SiO_2, about $4H_2O$.

Beidellite, Al_2O_3, with some Fe_2O_3, 3 or more SiO_2, about $4H_2O$.

Beidellite consists of isomorphous bodies containing both iron and alumina, intermediate between montmorillonite and nontronite.

All these have high base exchange capacity and similar X-ray spectra. Further they all show a phenomenon characteristic of this group only, that the lattice increases in one dimension as the water content of the mineral increases.

A number of these minerals have been synthesised by heating amorphous silica and alumina with water or sodium hydroxide solution to 300°-500° C. in a hydrothermal bomb.[1]

(3) Other minerals not yet identified, giving X-ray patterns somewhat similar to the montmorillonite group but not showing lattice swelling. This group includes " Ton Mineral X " of the German workers.[2]

(4) Hydrated ferric, aluminium, titanium and other oxides.[3]

So few clays have been fully examined that it is impossible to say how important any of these substances are in the soil. Hoffman and his co-workers found minerals of the montmorillonite group more common in tropical than in temperate soils, while temperate soils typically contained kaolinite often with appreciable quantities of " Ton Mineral X."

for soil investigators. It occurs in quantity in Canada and the United States and is the end product of the interaction between volcanic ash and the sea-water into which it fell.

[1] W. Noll, *Ztschr. Kryst.*, 1934, B, **45**, 175 ; *Neues Jahrb. Min. Beil.*, 1935, A, **70**, 65. In absence of alkali hydroxides he obtained kaolin, but in their presence montmorillonite was produced.

[2] *E.g.* A. Jacob, U. Hoffman, H. Loofman, and E. Maegdefrau, *Angew. Chem.*, 1935, **48**, 584. (Also published as *Beihefte zu den Ztschr. Ver. Deut. Chem. ; Verlag Chemie*, Berlin, 1935.)

[3] For details of the Russian work see A. A. Rode, *Trans. Dokuchaev. Inst.*, 1933, **8**, No. 3, and discussion in Antipov-Karataev, *Trans. Int. Soc. Soil Sci.*, Soviet Section, Vol. A, 1935, p. 80.

Structure of Clay Minerals.—In recent years W. L. Bragg [1] has applied X-ray methods to study the crystal structure of silicates and has shown that they are built up of a silicon-oxygen framework in which the silicon atoms are surrounded by four oxygen atoms in a tetrahedral arrangement, and the other cations take up various positions.

The silicon can to a certain extent be replaced by aluminium, beryllium, and possibly magnesium; and the oxygen atoms in a tetrahedron can be independent of each other, as in olivine, or they can be linked up through oxygen atoms belonging to two silicon atoms. They can then form independent groups, bands or chains of tetrahedra, as in the amphiboles and pyroxenes, or endless sheets as in the micas, or a three-dimensional network as in the felspars or in quartz.

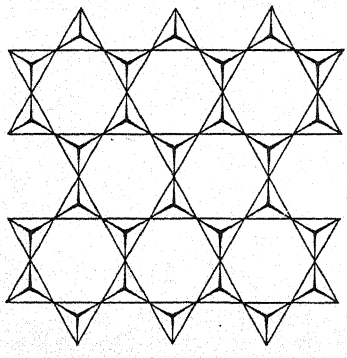


FIG. 18.—Silicon tetrahedra in hexagonal rings. E. Schiebold (*Naturwiss.*, 1932, 11, 352).

In the endless sheets, three of the four oxygen atoms of each tetrahedron belong to two groups simultaneously, being linked up to two silicon atoms, while the fourth has one end free and therefore a free valency for holding a cation. The groups themselves may form a hexagonal or pseudo-hexagonal pattern (Fig. 18) as in mica, or a pseudo-tetragonal pattern as in apophyllite. The silicon oxygen ratio for every sheet arrangement of this type is (Si_4O_{10}) or, if some of the silicon is replaced by aluminium $(Si, Al)_4O_{10}$.

These structures are based on X-ray measurements on single crystals and they have been determined with considerable accuracy.

The clay minerals, however, are not available in single-

[1] W. L. Bragg, *The Structure of Silicates*, 2nd edn., 1932, Leipzig; see also W. H. Bragg and W. L. Bragg, *The Crystalline State*, 1933, London.

crystals and X-ray measurements can be taken only by the powder method. This is trustworthy only for crystal structures of high symmetry, and the proposed structures for a number of clay minerals are therefore somewhat doubtful. A check by single crystal measurements has been possible for dickite, and this has confirmed the general features of the structure deduced from powder photographs but not the actual arrangement of the atoms in the sheets. Crystal structures have been suggested for kaolinite, nacrite, dickite, halloysite, montmorillonite, and nontronite.[1]

The kaolinite structure is built up of layers of silicon-oxygen tetrahedra in a pseudo-hexagonal pattern, as in the mica structure, alternating with aluminium hydroxide layers, identical with the layers of the hydrargillite structure, in which each aluminium atom is surrounded by six hydroxyls in an octahedral arrangement. One hydroxyl for each aluminium atom is replaced by the free oxygen from the silicon-oxygen layer, which is linked to one silicon atom only (Fig. 19). The chemical formula, corresponding to the structure is $(Al_4(OH)_8Si_4O_{10})$.

The structures for dickite and nacrite are essentially the same, but the arrangement of the layers on top of each other is slightly different: the details have been discussed by Gruner.

The montmorillonite structure suggested by Hofmann contains the same layers, but arranged in sandwiches, each aluminium hydroxide layer coming in between two silicon-oxygen layers. The corresponding formula is $Al_4(OH)_4Si_8O_{20}$. These sandwiches or compound layers have a thickness of

[1] For X-ray studies of the clay minerals see Hofmann, Endell, and Wilm, *Ztschr. Kryst.*, 1933, A, **86**, 340, and *Angew. Chem.*, 1934, **47**, 539 (montmorillonite); Marshall, *J. Soc. Chem. Ind.*, 1935, **54**, 393T, and *Ztschr. Kryst.*, 1935, A, **91**, 433, for details; A. Jacob, U. Hofmann, H. Loofmann, and E. Maegdefrau, *Angew. Chem.*, 1935, *Beihefte* **21**, 11; J. W. Gruner (kaolinite); E. Schiebold, *Naturwissenschaften*, 1932. See also C. J. Ksanda and T. W. F. Barth (*Amer. Minerol.*, 1935, **20**, 631) who have called these structures in question.

about 6·6 Å.,[1] and are separated by wider gaps containing water or air. The distance between them depends on the water content, varying from 3 Å. in the driest condition to

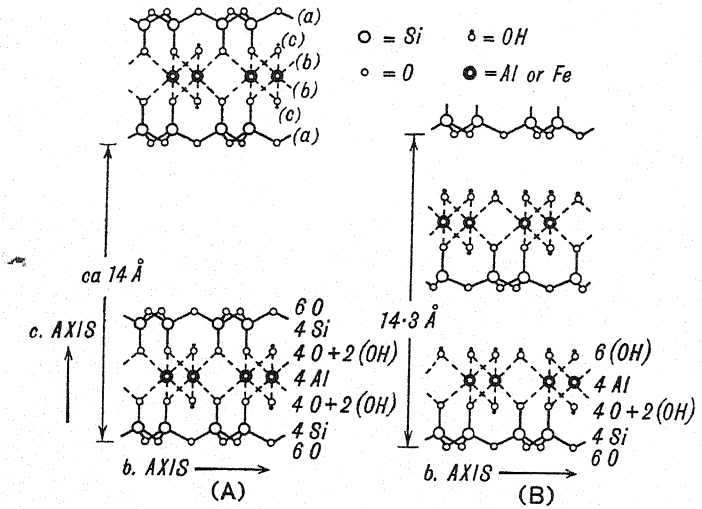


FIG. 19.—Crystal structure of (A) montmorillonite (U. Hofmann, K. Endell, and D. Wilm) and of (B) kaolinite (J. W. Gruner). A. Jacob *et al., Beihefte zu den Ztschr. Ver. Deut. Chem.*, 1935.

14 Å. in the wettest.[2] Gruner has shown that nontronite and probably beidellite have the same structure as montmorillonite, with iron and sometimes magnesium replacing aluminium, and aluminium and iron replacing silicon.

COMPARISON OF THE THREE METHODS OF ANALYSES.

These three methods, the mechanical, the chemical and the mineralogical, divide the soil up into a series of fractions, but in general a fraction classed by one method as homogeneous is shown by another to be heterogeneous. The separations employed in mechanical analysis are conventional; there

[1] Crystal dimensions are measured in Ångström units (Å.); 1 Ångström unit (Å.) = 0·1 mμ; 1000 mμ = 1μ = 0·001 mm. Diameter of hydrogen molecule = 0·24 mμ. Crystal lattice of sodium chloride = 0·28 mμ, *i.e.* 2·8 Ångström units.

[2] G. Nagelschmidt (*Ztschr. Kryst.*, 1936, A, **93**, 481) has studied this effect in some detail.

are no sharp divisions between sand and silt or between silt and clay. The distribution curve is a continuous function not only of particle size but of every other property also.

The chemical method is purely arbitrary; the different solvents attack to some extent all the fractions separated by mechanical analysis though in general they attack the finer more strongly than the coarser fractions. Thus Hissink showed that while "Silicate A" occurs largely in the clay considerable quantities may also be found in the silt and fine sand fractions. The solvents attack the surface of the particles, removing weathered material that may have accumulated on the surface and also some of the constituents of the crystal lattice (p. 167).

The mineralogical identification of the coarser fractions, especially after they have had their surface cleaned by a chemical solvent, is on the other hand, absolute. A given particle is either a felspar or it is not, though if it is a felspar its chemical composition and crystallographic properties may vary within wide limits. But the clay minerals cannot be completely separated nor can enough fundamental mineralogical constants be determined to show how far a given fraction is homogeneous.

General Properties of the Mineral Soil Constituents.

The Sand and Silt Fraction.

We can easily sum up the properties of the sand and silt fractions. They consist of resistant rock minerals, largely quartz, but with more or less of other minerals also.

Their chemical properties depend on their composition. When, as in the south-east of England, they consist almost entirely of quartz, they are inert, but when other minerals are present in quantity they may possess a certain base exchange capacity. In any case they constitute a framework on which substances may be precipitated from the soil solution or from percolating suspensions, and probably in natural

conditions they are never free from material of this sort. The oxidising and dispersing liquids used in mechanical analysis clean them to some extent.

The Clay Fraction.

(Particles below 0·002 mm. diameter.)

The clay fraction has been the subject of a vast amount of investigation. Unfortunately considerable confusion has arisen from the circumstance that the name "clay" is used in at least four different senses by different groups of workers. Soil investigators use it for all the mineral material of the soil the particles of which, if spherical, would be below 0·002 mm. diameter. Ceramic chemists, on the other hand, allow a much larger limit of size, 0·01 mm. diameter, but they restrict the name to a group of minerals of which kaolinite is the type. Geologists use the word in a third sense, and road engineers in a fourth. New names have at times been proposed to distinguish these substances but none have proved acceptable.

Particular attention has been paid to the characterisation of the clay fraction. A diameter of 2μ is now adopted as the most convenient size limit to take for the clay particles, but it is not a sharp limit. The crystalline portion of the clay fraction between 2μ and $0{\cdot}5\mu$ in diameter usually contains the same unweathered rock particles as does silt, in addition to the clay minerals. The fraction smaller than $0{\cdot}1\mu$ in diameter on the other hand probably contains in general only clay minerals. The distribution of non-crystalline and crystalline material in the different size fractions of the clay has not been properly investigated because of the lack of methods applicable to the finer fractions.

The colloidal properties are not sharply confined to the clay fraction. They become more pronounced as the particles become smaller, but there is no stage at which they suddenly appear. Beginning with the silt fraction they appear gradually as the particles become finer, though not

all at the same time nor do they all increase in the same way with increasing fineness. Some colloidal properties, such as base exchange, are often shown by the silt fractions, while others, like the power of forming gels, are shown only by the very fine particles and not by the coarser ones.

There has been much discussion as to whether the whole of the clay fraction or only part of it is responsible for its marked properties. One of the first fractionations of clay was made by Th. Schloesing in 1874.[1] He allowed a clay suspension to stand for several weeks, or if necessary, months, in order that the coarser material might be deposited; he then examined the material still remaining in suspension and found that it possessed colloidal properties in a high degree. He regarded the clay fractions as composed of fine inert particles bound by this cementing material which might, however, form only 1 or 2 per cent. of the whole.

The relative importance of the crystalline and non-crystalline constituents of the finer clay fractions in determining their colloidal properties is now under investigation. Some of the constituents have a lower base exchange capacity than the average for the fraction, as shown by the fact that treatment with weak solvents such as Tamm's acid oxalates, cold dilute oxalic acid, or Truog's reagent, dissolves out material and increases the exchange capacity of the residue. Roborgh also showed that repeated treatments with fairly concentrated warm hydrochloric acid and sodium carbonate at first increased the base exchange capacity of a Dutch clay from 42 to 50 milliequivalents per 100 grms. and then left it constant, although silica and alumina in constant ratio were still being dissolved out. He interpreted this as indicating that the crystals possess more power of base exchange than the material dissolved by the acid, which, he supposed, came from the superficial layers of the clay crystals. It is not certain whether amorphous silicates possessing base exchange of the type first postulated by van Bemmelen exist in the

[1] *C.R.*, 1874, **79**, 376 and 473.

soil or whether the properties of the clay crystals are determined in part by materials such as phosphates, silicates or aluminates absorbed on their surface, conferring on them amphoteric properties as discussed by Mattson (pp. 158, 218).

The Architecture of the Clay Particles.

The shape of clay particles is not definitely known, though there is much evidence that they are plate-like. Nor is it known for certain whether a clay particle has a permanent size; it is possible that the particles can readily cleave along their cleavage planes, and that treatment such as centrifuging in the Sharples super-centrifuge breaks many of them up. Mattson [1] has suggested that the size of a clay particle depends on the exchangeable ion in the clay, and is smallest for the sodium and lithium clay and largest for the calcium.

The location of the exchangeable ions in the clay particles is still the subject of some controversy. Marshall [2] has argued that the exchangeable ions occupy definite positions in the clay lattice, because he found that the double refraction of suspended clay particles varied with the exchangeable ions on the clay; and he interpreted the result to indicate a change in the optical properties of the lattice itself, and not merely a change in the surface conditions. He considers these ions are situated in the space between successive sandwiches in the clay lattice.

The alternative view is that the exchangeable ions are on the outer surface of the clay particle. All the exchangeable cations of clay can be replaced rapidly and completely by large cations such as methylene blue [3] and the hexammine cobaltic ion: [4] they must therefore be in some very accessible position. On the other hand these large ions cannot effect

[1] *Soil Sci.*, 1929, **28**, 373.
[2] *Trans. Faraday Soc.*, 1930, **26**, 173, and *Ztschr. Kryst.*, 1935, **90**, 8.
[3] M. S. Anderson and S. Mattson, *U.S.D.A. Bull.* No. 1452, 1926.
[4] H. Paver and C. E. Marshall, *Chem. and Ind.*, 1934, **12**, 750.

exchange with permutites and zeolites: it is assumed that these substances hold their exchangeable ions in pores too narrow for large ions to enter.[1] Kelley and his co-workers [2] have obtained further evidence that the exchangeable ions are on the outside of the clay particles. They showed that the base exchange capacity of minerals and clay colloids was increased by grinding in a ball mill provided the crystal structure was one that could hold exchangeable bases. They obtained evidence of two ways in which exchangeable bases could be held by the lattice: either by the net negative charge on an Al tetrahedron, *i.e.* by a group of four closely packed oxygen atoms containing an Al ion in the central interstice; or by replacement of a H from an —OH group on the surface of the lattice: these latter groups may either exist in OH—Al—OH planes (*c* in Fig. 19, p. 176) or be produced by breaking a Si—O—Si or an Al—O—Al bond (*a* and *b* respectively in Fig. 19), leaving 2Si—OH or 2Al—OH groups. The more finely these minerals are ground, the larger is the proportion of these groups or broken bonds that appear on the surface and the larger the exchange capacity.

They further showed that after grinding the clay some of the bases held in the lattice itself became exchangeable and some only displaceable. Clays may contain appreciable quantities of potassium and magnesium in non-exchangeable form, and the potassium and some of the magnesium in the lattice probably neutralise the negative charges on the aluminium tetrahedra; these bases can apparently become exchangeable as soon as they are sufficiently near the surface. But magnesium can also replace Al in its 6-co-ordinated position to form the brucite structure, and while after grinding, this magnesium can be displaced by salts such as ammonium

[1] N. C. Cernescu, *Anu. Inst. Geol. Român.*, 1931, **16**.

[2] W. P. Kelley, H. Jenny, and S. M. Brown, *Soil Sci.*, 1936, **41**, 259; W. P. Kelley, H. Jenny, *ibid.*, 367. See, however, Drosdoff, who confirmed the increased solubility after grinding but found no change in the exchange capacity (*ibid.*, 1935, **39**, 463).

acetate, it is not exchangeable since no ammonium ions are taken up.

Kelley's experiments indicate therefore that the exchangeable bases are held by primary valencies on the surface of the clay crystals. If held in definite positions on the surface, as is not improbable, they may be able to cause the double refraction phenomena noted by Marshall.

The Clay Acid.—The preparation and properties of acid clays are similar to those of acid soils, which have already been described. The surface of the acid clay particle contains exchangeable hydrogen ions which can dissociate when the acid is suspended in water but can never move far from the particle surface. They can affect an electrode placed in the suspension and can invert cane sugar, but they must move with the particle. When the particle sediments it carries its cloud of hydrogen ions down with it. Thus the *p*H of the acid clay is often about 3 to 3·5, while the liquid in which it is suspended when separated by ultra-filtration may be almost neutral.[1] The clay acid probably also contains exchangeable aluminium,[2] which unlike the other exchangeable cations, may arise from the clay lattice by hydrolysis.

The strength of the clay acid cannot be rigorously specified since no sufficiently precise physico-chemical description of insoluble and colloidal acids has yet been found. An approximate comparison with a simple acid can be made if the buffer curve of the clay acid possesses one or more marked points of inflection, although the analogy cannot be taken far. The curve for the English subsoil (Fig. 16, p. 155) has two points of inflection, *i.e.* two ranges of maximum buffering, one a little below *p*H 3 and one about *p*H 10 ; it is therefore comparable with a dibasic acid whose first dissociation constant is of the same order as that of lactic acid and whose

[1] R. Bradfield, *Proc. 1st Int. Cong. Soil Sci.*, Washington, 1927, **2**, 264.

[2] H. Paver and C. E. Marshall, *Chem. and Ind.*, 1934, **12**, 750. See also S. Mattson, *Soil Sci.*, 1928, **25**, 345.

second is about the same as the second dissociation constant of carbonic acid. It is not possible to say much more because the curves for these simple acids differ in shape from the soil curve. The South African subsoil has only one range of maximum buffering at about *p*H 9, which is comparable with boric acid ; while the acid of the peat has no marked region of maximum buffering, but this increases almost continuously as the *p*H rises and so is not comparable with any single simple acid.

The inadequacy of the physico-chemical theory of insoluble or colloidal acids also makes it impossible to give a rigorous definition of the equivalent weight of the clay acid. By analogy with soluble acids the English subsoil possesses an equivalent weight for the neutralisation of each of its two basicities, the South African subsoil has one equivalent weight, while the peat cannot be said to possess any equivalent weight. Some workers have defined the equivalent weight of the clay acid as the weight of clay holding one equivalent of base under certain specified conditions. D. J. Hissink determined the weight of clay holding one equivalent of barium when in equilibrium with 0·1*N* $Ba(OH)_2$ (*p*H between 12-13) while P. E. Turner mixed his soils with $CaCO_3$ and leached with NaCl (*p*H about 8). Their results for the equivalent weight of clays [1] were :—

		Mean.	Outside Values.
Hissink [2]	Dutch clays . . .	1225	1033-2061
Turner [3]	Trinidad, West Indian clays	4100	—

These figures simply express the base exchange capacity of the clay, and as this varies widely with different clays, estimates of the equivalent weight are no longer made. Recent workers prefer to use the base exchange capacity.

[1] For humus figures see p. 204.

[2] *Trans. Faraday Soc.*, 1925, **20**, 551 ; *Trans. II. Comm. Int. Soc. Soil Sci.*, Groningen, A, 1926, 198.

[3] *J. Agric. Sci.*, 1932, **22**, 72.

INFLUENCE OF THE SILICA/SESQUIOXIDE RATIO OF THE CLAY ON THE EXCHANGE CAPACITY AND RELATED PROPERTIES.

Many researches have been made on the influence of the silica/sesquioxide ratio of the clay on its colloidal properties. On the whole clays with a high silica/sesquioxide ratio have higher exchange capacity up to *p*H 7 than clays with a lower

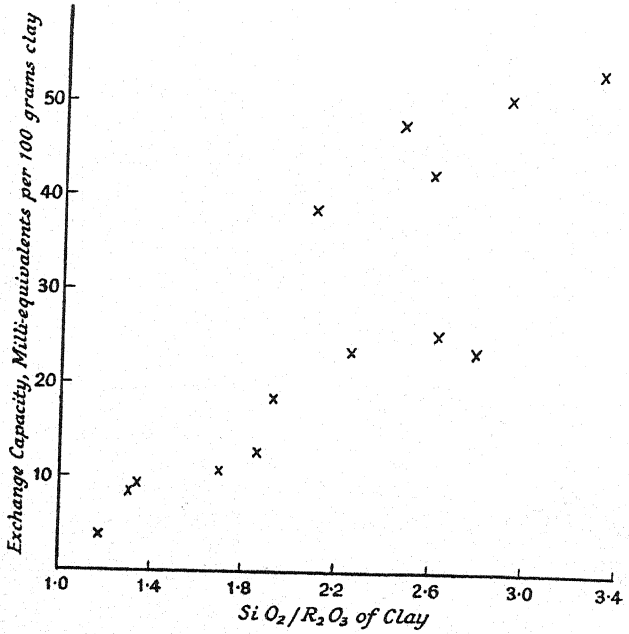


FIG. 20.—Relation between chemical composition of clay and its exchange capacity (F. W. Parker and W. W. Pate).[1]

ratio (Fig. 20). The relationship is fairly close for some series of clays especially if only the fine fractions are considered, and it may result from the circumstance that the clay minerals of high exchange capacity (montmorillonite and " Ton Mineral X " group) have also high silica/sesquioxide ratios while those of low base exchange capacity (the kaolin group, the iron and aluminium hydroxides) have low ratios.

There are, however, many exceptions to the rule, and

[1] *J. Amer. Soc. Agron.*, 1926, **18**, 470.

no completely satisfactory explanation can be given. The silica/sesquioxide ratio is not so closely related to most of the clay properties as is the exchange capacity (Fig. 21 and pp. 154, 224).

Physical Properties of the Clay-Water System.

The common clay properties are associated with the water present and are more properly described as properties of the clay-water system.

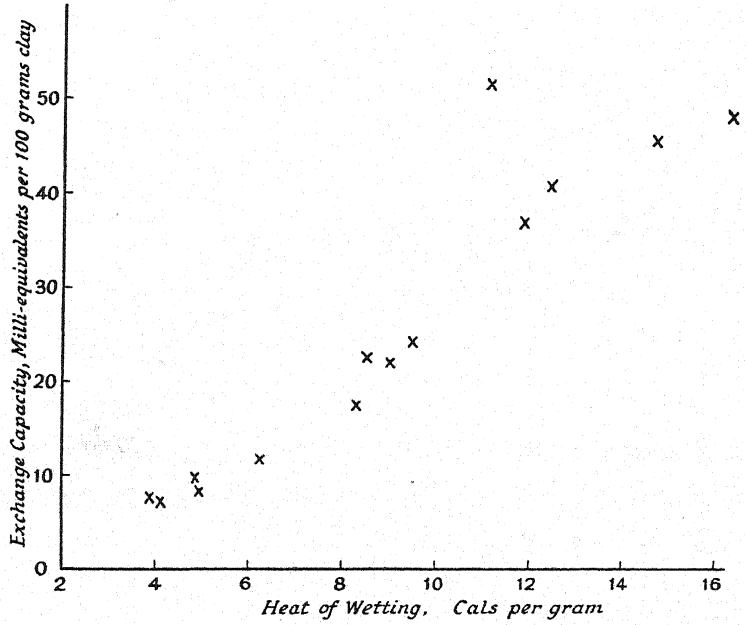


FIG. 21.—Relation between exchange capacity of clay and its heat of wetting (F. W. Parker and W. W. Pate).

Four cases have been studied :—

(1) *Water in Great Excess.*—When an acid clay is fully dispersed in a large volume of water containing a little caustic soda and stirred, the stream usually has the silky appearance characteristic of non-spherical particles. On standing, the larger particles slowly settle, forming a sediment the characteristic properties of which are that it is compact and difficult to redisperse. The muddy suspension is darker in colour at

the bottom than at the top, but it generally shows no sharp transition layers. It is said to be deflocculated.

Addition of sufficient electrolyte clarifies this suspension; individual flocs are formed, which settle to a loose voluminous sediment, leaving the dispersion liquid above clear. The suspension is said to be flocculated. The characteristic properties of the sediment are that it is voluminous and redisperses easily on shaking.

These phenomena can be pictured somewhat as follows. In the dilute deflocculated suspension each individual micelle with its diffuse cloud of dissociated cations is settling under the influence of gravity and in addition moving with the convection currents of the liquid as well as with its appropriate Brownian motion. Each micelle moves independently of the others unless two approach closer than a certain distance, when they move away from each other as if they had suffered an elastic collision. When the suspension is flocculating, however, the colliding particles stick together in some or all of these collisions till finally the complex aggregates become so large that they appear as flocs.

In the deflocculated suspension the clay particles had settled into closest packing; in the flocculated suspension, on the other hand, the clay flocs settle into a very loose formation, possibly forming open chains and rings, and they enclose a large volume of dispersion liquid. The detailed mechanism which allows the clay particles to form this open network is unknown.

The persistence with which a clay remains deflocculated depends on its exchangeable ions and on the substances dissolved in the water. The general effects are well established but not the details, and recorded experimental results are often confused by some uncontrolled secondary action.[1]

The exchangeable ion held by the clay markedly affects the stability of the suspension. Lithium and sodium clays are

[1] For a discussion of the detailed results see G. Wiegner, *J. Soc. Chem. Ind.*, 1931, **50**, 65T, and E. W. Russell, *J. Agric. Sci.*, 1932, **22**, 165.

more resistant to flocculation than others: the order of resistance is

$$Li > Na > K > Mg, Ca \text{ and } Ba.$$

The stability of the H-clay is probably comparable with that of the Ca-clay.

The flocculating power of simple salts depends on their metallic cation and on any secondary reactions that may occur between them and the clay. Chlorides present the simplest case, base exchange being usually the only important secondary action taking place. Among the alkali metals, lithium chloride is the weakest and cæsium chloride is the strongest flocculent; the order is

$$Li < Na < K < Rb < Cs.$$

Of the alkaline earth metals, magnesium chloride is probably the weakest though it is stronger than most of the alkali chlorides; and barium is the strongest with calcium intermediate. Aluminium and iron chlorides are still more powerful flocculants, but important secondary actions result from the high hydrogen-ion content of their solutions. The nitrates and sulphates behave similarly to the chlorides. Soluble carbonates, such as sodium carbonate, react with the alkaline earth clays to give sodium clay and the insoluble alkaline earth carbonate before any flocculating action can take place, and complex or polyvalent anions such as silicates or phosphates are absorbed on the clay surface and so alter its properties.[1]

(2) *Concentrated Clay Suspensions* (*about* 0·5 *to* 5 *per cent.*).[2] Electrolytes can cause two types of flocculation in fairly dilute clay suspensions (*e.g.* 0·5 per cent.). At low electrolyte concentrations fine flocs are formed which settle through

[1] See, for example, A. Demolon and E. Bastisse, *Ann. Agron.*, n.s., 1933, **3**, 73.

[2] R. K. Schofield and B. A. Keen, *Nature*, 1929, **123**, 492; R. K. Schofield and G. W. Scott Blair, *Trans. Faraday Soc.*, 1931, **27**, 629; J. L. Russell, *Proc. Roy. Soc.*, 1936, A, **154**, 550.

the turbid suspension. Above a certain critical concentration, however, the whole system sets to a thixotropic [1] gel which settles leaving a clear liquid. This gel is usually very weak, and the clear liquid, as it separates out in the interior and rises, breaks it up into floccules which settle to a more compact and stronger system. But there is a range of electrolyte concentrations which is fairly wide for sodium clays and probably for potassium clays in sodium chloride, and very narrow for sodium clays in calcium chloride, at which the gel is strong enough to retain its shape during contraction, and is sufficiently rigid to retain any mark made on its surface. As the clay concentration increases or the clay particles become smaller the gel becomes stronger over a wider range of electrolyte concentration and the first type of flocculation, *i.e.* the breaking of the gel into floccules becomes less pronounced.

The more compact system formed after the breaking up of the first thixotropic gel settles slowly, and the liquid which separates out inside the mass rises along narrow channels carrying some floccules with it, and forms holes surrounded by little mounds on the clay surface (Fig. 22). The clay concentration of this system increases slowly with time, but is almost independent of the electrolyte concentration, and is nearly the same for calcium, barium, and hydrogen clays.

For more concentrated suspensions, which can easily be prepared since even a concentrated deflocculated clay suspension is still very fluid, the main effect of adding an electrolyte is to increase the thickness of the suspension, which is probably converted to a stiff thixotropic gel. A little liquid separates out in this semi-rigid gel and escapes, leaving holes about 1 mm. or a little less in diameter over the surface. These holes no longer have little mounds around them since the gel is too rigid for the escaping liquid to break off any floccules. Cracks, several centimetres deep, may also develop, and persist for several months without closing up.

[1] A gel is said to be thixotropic if it behaves on shaking as a liquid, but on standing as a jelly.

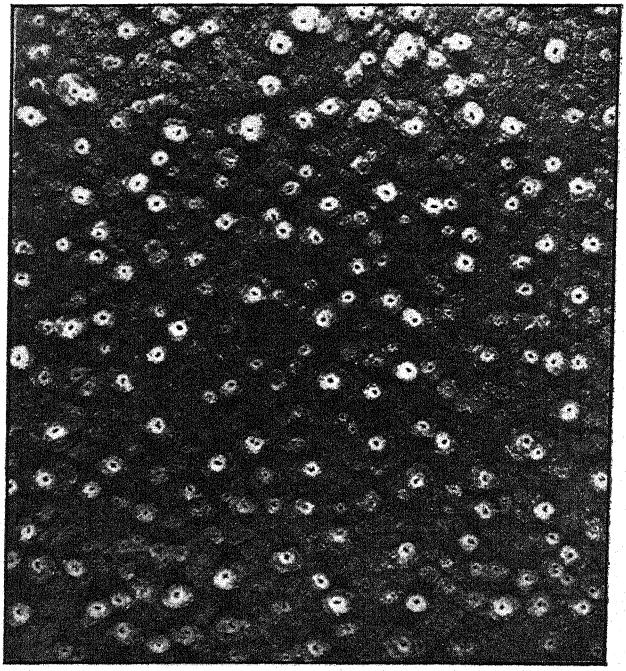


FIG. 22. Perforated mounds formed at the surface of a settling clay suspension, showing its rigidity.
(Schofield & Keen.)

Deflocculation may be difficult to recognise in concentrated clay suspensions. The silky appearance on being shaken is the best indication; a very small quantity of electrolyte suffices to make it indistinct. But some clays do not show this phenomenon, and for these there is no simple method of distinguishing a properly deflocculated clay from one only in part deflocculated.

(3) *Clay Pastes.*—Ceramic workers have done much work on the properties of ceramic clay pastes, but their results cannot be applied directly to the soil. G. W. Scott Blair has, however, worked with soil clays, and has studied the rate of flow of the clay paste through a narrow tube under a certain stress or driving pressure.

Up to a certain critical stress the paste does not move at all. Under greater stress it slides as a solid plug through the tube, being lubricated by a thin envelope of liquid. Assuming the envelope to be of constant thickness, an equation of flow can be derived which adequately fits the data, although in point of fact the layer is not constant in thickness. At another sharply defined stress, called the critical shearing stress, the paste starts to flow like a fluid. The region of fluid flow, initially confined to the neighbourhood of the wall, gradually extends until almost all the material is flowing in streamline fashion. In many cases, however, even at these stresses, the laws of ordinary fluid flow cannot be applied without modification. Thus the paste flows more rapidly in narrow tubes than would be expected from theoretical considerations. If one assumes that flow is abnormally easy in a region near the tube walls it becomes possible to derive an equation that is consistent with the facts. The physical nature of the process is, however, not fully understood.

These phenomena are linked up with certain other clay properties. A paste made from soil that had been dried, did not show the effect of a plug flowing through the liquid envelope. Further, the variations in resistance to the plough in different parts of a field were closely correlated with

variations in the critical shearing stresses of pastes made from the different samples of soil.[1]

As the proportion of water becomes less and the mass more nearly approaches a soil in consistency, the properties are governed by the circumstance that two sets of factors are involved: the water films, which exert a dominant influence at high water content; and the solid clay, which dominates at low water content. These effects overlap, and so far no clear breaks have been recorded. Haines showed, for example, that the plasticity curves are continuous from wet to dry clay, though in wet conditions the clay was tough and in dry conditions it was brittle. The phenomena vary in degree according as one is passing from a dry state to a wet one or *vice versa:* at any particular water content a clay may therefore have two sets of values for certain of its physical properties.[2] In his plasticity studies Atterberg[3] had found breaks showing where the water films ceased to dominate, but Haines found none. On the other hand, G. H. Cashen obtained evidence of four critical moisture contents at which the electrical conductivity of the soil showed breaks. Two of these appeared to agree with the Atterberg breaks, while two were new.[4] The property of stickiness also appears to be an exception to the rule of gradual transitions. Dry soil is not sticky, but when more and more moisture is added a point is reached where its particles suddenly stick to a kneading implement. Hardy regards this as the point where the soil colloids have absorbed water to their maximum capacity, so that there is now free water over which the particles can slip: this simple view, however, is not universally accepted.

(4) *The Solid Mass. Crumb Formation.*—As the proportion of water becomes less the clay particles approach more

[1] G. W. Scott Blair, *Trans. VI. Comm. Soil Sci.*, 1932, A, p. 246; with E. M. Crowther, *J. Phys. Chem.*, 1929, **33**, 321; with B. A. Keen, *J. Agric. Sci.*, 1929, **19**, 684.

[2] See also p. 515.

[3] *Int. Mitt. Bodenk.*, 1911, **1**, 10.

[4] *J. Agric. Sci.*, 1932, **22**, 145.

closely and they unite to form "crumbs." The phenomena have been studied by E. W. Russell [1] who shows that it is dependent on the presence of sufficient exchangeable ions in the clay. Crumb formation does not occur, however, when the ions are large, nor when other liquids replace water, excepting only to the extent that the molecules of the liquids are, like those of water or methyl alcohol, small and polar.[2] Thus no crumbs are formed by clays with large complex organic cations, nor when clays are wetted by non-polar liquids, *e.g.* carbon tetrachloride, benzene, etc., or polar liquids with large molecules such as amyl alcohol; in all these cases the clay simply falls down to a fine powder.

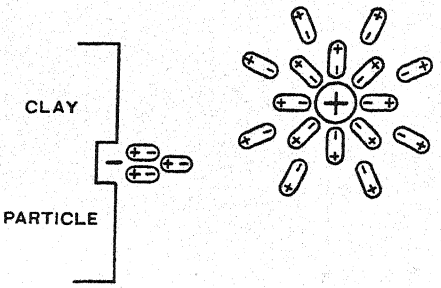


FIG. 23.—Diagrammatic representation of a clay micelle dispersed in water (Russell).

E. W. Russell pictures the process as follows. The cations of the clay orientate the polar molecules of the liquid around them with an intensity which increases with their surface density of charge. The negative charges on the micelle do the same, so that a clay micelle suspended in a large volume of water can be represented diagrammatically as in Fig. 23. As the quantity of liquid decreases, a cation can attract polar molecules already orientated by two different clay particles, thus building up an orientated chain which restricts the free motion of all its components; the system therefore

[1] *Phil. Trans. Roy. Soc.*, 1934, A, **233**, 361.

[2] A polar molecule is one in which the electrical charges are not distributed evenly, but one end of the molecule has a net positive and the other a net negative charge.

begins to acquire rigidity. With further loss of liquid all the remaining molecules become tightly held and the system forms dry crumbs (Fig. 24). More complicated orientated chains can be built up at high water contents if an electrolyte is added, and the rigidity greatly increases. The system is thixotropic, for on shaking sufficiently vigorously the orientated chains are broken down, making the suspension behave as a liquid, while on standing the chains are reformed making it behave as a jelly.

The factors determining crumb size are mainly unknown.

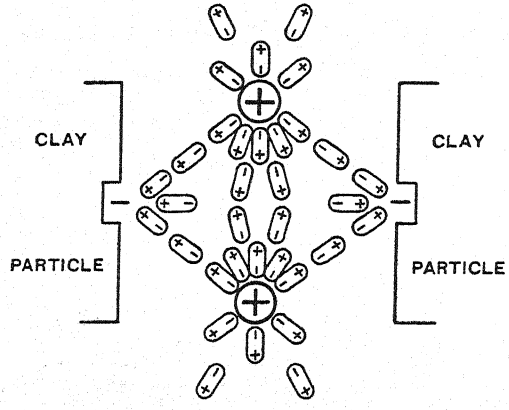


FIG. 24.—Diagrammatic representation of two clay micelles held together as in a crumb (Russell).

The crumbs are in general small if the clay particles are small or if the clay paste has been rapidly frozen, as for example in liquid air, or if a high concentration of salt is present.

The mechanical strength of soil crumbs is largely determined by the base exchange capacity. Soils of low base exchange capacity, such as sandy, silty, and kaolinitic soils, form only weak crumbs, as also do saline soils, presumably because the salts depress the dissociation of the exchangeable cations from the clay, and so reduce the number of binding links between the clay particles.

One of the most important agricultural properties of crumbs

is their stability in water. A stable crumb retains its individuality when wetted with water, while an unstable one falls down to a paste. Crumbs formed in calcium or acid soils are usually water stable, but sodium and in some conditions potassium soils give crumbs unstable in water. Crumbs of a sodium soil wetted with water fall down to a paste which dries to large, hard lumps; they remain stable, however, in a sufficiently concentrated salt solution, *e.g.* in *N* NaCl solution. The cause of water stability is not known, but it appears to be connected with the flocculation properties of the clay paste. Crumbs made from a flocculated paste are always stable; those from a deflocculated paste may be unstable, though they are not necessarily so.

At first sight it might be supposed that the crumbs are the same as the flocs formed in dilute suspension but they seem to be entirely different. Floc formation is best developed in the presence of adequate amounts of electrolyte, while crumbs have their maximum stability in the absence of electrolyte. Flocs have a very open heterogeneous structure, and a large volume in comparison with their component particles; crumbs have a much closer, more homogeneous structure and can be more strongly held together.

Effects of the Various Fractions on the Fertility of the Soil.

The most reliable methods of estimating the effect of individual fractions on soil fertility are statistical. So far these have not been much used. Numerous field observations have been made and there is little doubt as to their general accuracy, but no definite proof can be given.

The Sand and Silt Fractions.

Their characteristic property is inertness. When separated from the soil in a clean state sand shows no colloidal properties, no power of absorbing water or dissolved substance, no cohesion or plasticity; and silt shows very little. These negative

properties, however, are very important in the soil. The particles being irregular in shape do not pack closely together, so that large pore spaces are left which facilitate aeration, drainage, and leaching. Where, however, the silt particles are plate-like, they can pack together and much impede drainage.

In natural conditions the silt and sand particles in the soil are not clean, and it needs only a very small quantity of clay absorbed on their surfaces to confer a considerable degree of colloidal properties on them.[1]

The Clay Fraction.

In contrast to the inertness of the coarser fractions, clay is active, both physically and chemically. Hence the clay properties are of great importance to the fertility of the soil, and no constituent is more necessary in proper proportions, or more harmful in excess. Clay impedes the movement of water in the soil and keeps it in the surface layers within reach of the plant roots, thus making the soil retentive of water. Excess of clay, however, interferes too much with the water movements, parching the soil in dry seasons, even though the permanent water level is near the surface, but making it water-logged in wet weather, thus impeding the movement of air to the roots and lowering the temperature of the soil. The adhesive properties of clay cause the soil particles to bind together into those aggregates on which "tilth" depends; soil without clay would be very like a sand heap. Here also, however, excess of clay does harm and makes the soil so adhesive that it sticks to the tillage implements and retards their movements; it also tends to form large clods unfavourable to vegetation. These effects are intensified in wet weather; the soil becomes sticky and must not be worked or the tilth is injured for a long time. Another effect of a large amount of clay is to make the soil shrink very much on

[1] J. Dumont, *C.R.*, 1909, **149**, 1087; H. Freundlich and F. Juliusburger, *Trans. Faraday Soc.*, 1935, **31**, 769; J. L. Russell and E. K. Rideal, *Proc. Roy. Soc.*, 1936, A, **154**, 540.

drying, so that large cracks appear in the fields in summer time. The swelling of the clay in wetting may be harmful.[1]

In addition to these purely physical effects, the chemical properties of clay as a complex mineral and an insoluble acid play an important part in soil fertility. Clay slowly weathers, liberating potash and other substances necessary for plant growth. Its base exchange properties enable it to retain in an available form plant nutrients such as potash, lime, and ammonia, protecting them against rapid washing out from the soil. When long-continued leaching with acid water has removed the bases, the resulting acid clay has great buffering power. Consequently more lime is required to bring a clay soil back to neutrality than a sandy soil of the same degree of acidity.

Heavy clay soils can be made more workable by large dressings of chalk, continued dressings of farmyard manure, or leaving the land for some years in undisturbed grass; on the other hand, the difficulties of cultivation are intensified by the excessive or improper use of liquid manure or of sodium nitrate.

In England, as a rule, 8 to 16 per cent. is a satisfactory proportion of clay in a soil where the rainfall is 25 to 30 inches per annum; higher proportions up to 40 per cent. occur on Lower lias and London clay soils, but not as a rule on the soil derived from the older rocks of the western counties and of Wales.

Soil Organic Matter.

The organic matter in soil is derived almost entirely from plants and micro-organisms: only a small amount comes from the bodies of animals. It ranges from fresh material, containing the same substances as the living plant or organism, down to very ancient material, going back, in the case of

[1] When the Gezira (Sudan) was first irrigated, the swelling of the clay was so great as to force the masonry of the regulators out of position, sometimes as much as 10 cms., thereby causing considerable trouble.

sedimentary rocks, to the time when they were deposited; many soils contain appreciable quantities of coal and charcoal fragments. A complete study of the soil organic matter would cover a large part of organic chemistry. Many of the compounds occur only in small amount and are generally disregarded by soil investigators: so far as is known they are without effect on the growing plant, though it is by no means certain that they are all inert.

Under similar soil and climatic conditions there is a tendency to similar ratios of carbon and nitrogen in the total organic matter of the soil after picking out obvious plant fragments.[1] For the cultivated soils of temperate climates this ratio is usually about 10: in arid regions it tends to be less. N. P. Remezov[2] found a fairly regular sequence in passing from the northern forests to the southern deserts of Russia:—

	C/N Ratio.
Podzolised soils	6·8
Grey forest soils	8·0
Chernozems	9·7
Chestnut soils	6·8
Grey desert soils	4·5

Within the chernozem belt the ratio increased with decreasing mean annual temperature:—

Azov	Ukraine	Russia (R.S.F.S.R.)	Siberia
6·2	7·6	11·4	13·6

The characteristic part of the organic material is, however, the black substance known as "humus," which is colloidal, possesses considerable power of absorption and after removal of calcium is acid. In normal conditions it contains

[1] The unchanged plant material can also be dissolved out by acetyl bromide, and this reagent has been used by certain investigators, *e.g.* Karrer and Bodding-Wieger, *Helv. Chem. Acta*, 1923, **6**, 817; U. Springer, *Ztschr. Pflanz. Düng.*, 1928, A, **11**, 313; 1931, **22**, 135; W. Grosskopf, *Sudetendeut. Forst- u. Jagdztg.*, 1931, p. 33.

[2] *Ztschr. Pflanz. Düng.*, 1933, A, **30**, 285 and 299; see also M. S. Anderson and H. G. Byers, *Soil Sci.*, 1934, **38**, 121.

about 56 to 58 per cent. of carbon [1] and about 5·5 per cent. of nitrogen. This material is fairly easily oxidisable. W. McLean [2] at Bangor fractionated the soil organic matter as follows :—

(1) Oxidised by 3 per cent. H_2O_2: this accounts for about 85 per cent. of the carbon and of the nitrogen in the soil. It contains nitrogen roughly in the proportion 10C : 1N.

(2) Oxidised only by 6 per cent. H_2O_2: this fraction is apparently free from nitrogen.

(3) A resistant fraction containing nitrogen, which is not attacked even by repeated treatment with 6 per cent. H_2O_2.

The large easily oxidised fraction probably corresponds fairly closely with the " humus."

From the earliest days chemists have been interested in this humus, but it has proved peculiarly elusive. The work began with Vauquelin, who, in 1797, found that some of it could be extracted by alkali after the soil had first been treated with an acid.[3] Sprengel (1826), one of the earliest and most successful investigators in agricultural chemistry, had in 1826 carried his studies so far that little has been added since ; [4] he distinguished the " acid humus " of peat found in places where bases are lacking, and giving the peat its acid reaction, from the less acid " mild humus " formed in soils in presence of basic material ; the " acid " is much more stable than the " mild " form, being less easily decomposed to carbon

[1] The older chemists sometimes estimated humus by determining the organic carbon and then multiplying this figure by 1·72, which corresponds to 58 per cent. in the humus. No advantage, however, was gained by doing this, and it is no longer done.

[2] *J. Agric. Sci.*, 1931, **21**, 251. [3] *Ann. Chim.*, 1797, **21**, 39.

[4] A full account of Sprengel's work is given by S. A. Waksman in his admirable summary of the literature in his book, *Humus* (Ballière, Tindall & Cox, London, 1936). Waksman points out that Sprengel's work has generally been overlooked, credit being given instead to Mulder, who, however, came later.

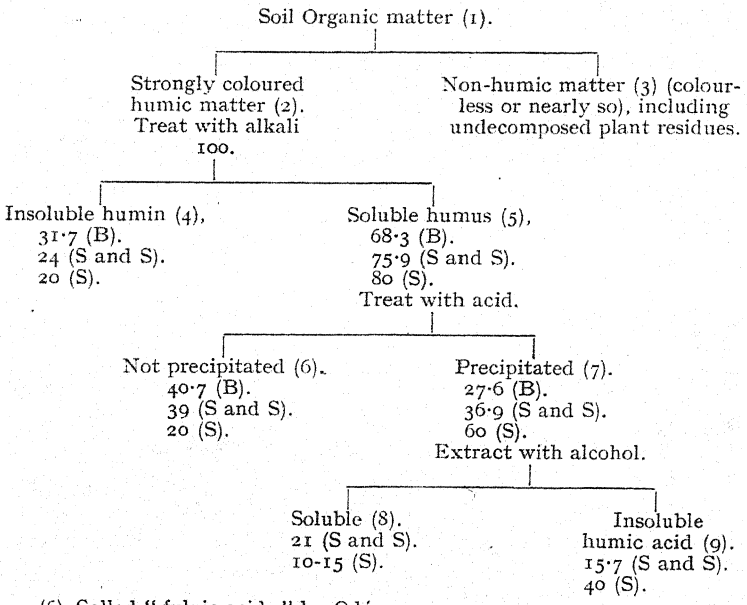
dioxide and water. He prepared humic acid by extracting the peat with dilute hydrochloric acid for two hours to remove all bases, washing with water, then extracting with a solution of ammonia in a closed vessel, finally adding to the solution hydrochloric acid to precipitate the humus. It did not, however, come down pure, but contained both clay and ferric hydroxide; it was therefore redissolved in sodium carbonate solution, filtered and precipitated from the filtrate by cold hydrochloric acid.

It was now nearly free from ash constituents: it was black, and when washed free from acid dissolved slightly in water; on electrolysis it travelled to the positive pole, being thus electronegative like other acids. It formed salts with bases: soluble ones with alkalis, and insoluble ones with alkaline earths and heavy metals. It liberated carbon dioxide from carbonates and silicic acid from soluble silicates; further, it combined with clay and with iron oxide. When dried it became shiny black, easily pulverised and highly absorbent of water, but it was now quite insoluble in water. A similar substance was prepared with potassium hydroxide solution in presence of air—the oxygen was supposed to play some part.

Extensive investigations by G. J. Mulder[1] confirmed these results but carried things no further; indeed, little was added till quite recently. Sprengel's "humic acid" was shown to contain something soluble in alcohol; also that part of the soil organic matter insoluble in the sodium hydroxide solution—Berzelius' "humin"—was found to become soluble after treatment with boiling alkali. The divisions usually adopted have been :—[2]

[1] *Liebig's Ann. Chem. Pharm.*, 1840, **36**, 243; *J. prakt. Chem.*, 1840, **21**, 203 and 321; *Die Chemie der Ackerkrume*, Berlin, 1861-1862.

[2] H. J. Page, *J. Agric. Sci.*, 1930, **20**, 455. The figures in brackets are for the purpose of identifying the fractions: those not in brackets are explained in the text.



(6) Called " fulvic acids " by Odén.
(8) Called " hymatomelanic acid " by Hoppe-Seyler and Odén, but now known to be a complex mixture.

The figures under the names of the fractions show how the carbon is divided between them: Berthelot and André's results are marked (B), Schreiner and Shorey's (S and S), and A. Shmuk's (S).[1] None of these fractions, however, is a simple body. Schreiner and Shorey in a classical investigation (1910) isolated a large number of compounds from the part soluble in alkalis (fraction 5). Improvements in the technique have been introduced by Page [2] and by K. Simon,[3] who begins by removing unchanged plant material with acetyl bromide and then goes on to use gentle extracting media such as slightly neutral or slightly acid fluorides and oxalates.

[1] *Pedology*, 1930, **25** (3), 5. From fraction 7 he extracts by means of various solvents Schreiner and Shorey's resin acids and accompanying substances, amounting to 5 per cent. of the original carbon. The residue is then extracted with alcohol to give fractions 8 and 9.

[2] *J. Agric. Sci.*, 1932, **22**, 497.

[3] *Ztschr. Pflanz. Düng.*, 1934, A, **34**, 144.

Odén (1919), using physico-chemical methods, showed that the insoluble humic acid (fraction 9) possessed all the properties of an acid: it had *p*H values 3·9 to 4·5. He regarded it as a single body, free from nitrogen, tetrabasic, with molecular weight of the order of 1350 and equivalent weight 340; he even suggested a formula $C_{60}H_{52}O_{24}(COOH)_4$. Other investigators regard it as a mixture with no definite basicity: their estimates of the equivalent weight are about 600, *i.e.* double those of Odén (p. 204)

Numerous attempts have been made to synthesise humic acid, and a number of substances have been prepared from furfural, sugar and other carbohydrates similar to it in colour and in general appearance. Unfortunately, no good methods could ever be devised for purifying or for definitely characterising these substances, so that no certain information about soil humus could be deduced from them. Such comparisons as were made, however, indicated that the synthetic substances differed in various ways from soil humus.[1] For some years past these efforts have been abandoned. Many hypotheses were also put forward about the constitution of humus; the most interesting, because of its similarity to the view now common, being that of Hébert and Dehérain [2] that humus is an association of lignin with proteins synthesised by bacteria.

The humic acid extracted by alkali after preliminary treatment with acid is probably not far removed from soil humus; samples from different soils are not identical but they agree in so many of their properties that some underlying unity may be assumed. Thus a plot on the Broadbalk wheat field at Rothamsted that has received farmyard manure each year for the past eighty years, and carries wheat every year, contains much more organic matter than the Barnfield plots receiving no farmyard manure, but only the leaves of the

[1] H. J. Page, *J. Agric. Sci.*, 1932, **22**, 291.

[2] A. Hébert, *Ann. Agron.*, 1892, **18**, 536; P. P. Dehérain, *Traité de Chimie Agricole*, Paris, 1892,

mangolds grown upon them; the difference in cultivation is considerable. Yet no difference in the composition of the organic matter can be detected.[1]

The humic acid contains nitrogen removable only by rather drastic means: Odén succeeded in obtaining it almost nitrogen-free, but Page and his assistants at Rothamsted were unable to remove the nitrogen by any gentle treatment; some 5 per cent. always remained. On hydrolysis this nitrogen complex breaks up into the same groups of substances as does plant protein, and the proportions of the different groups are not widely dissimilar in the two cases.[2]

The composition of the humic acid obtained by Page and du Toit was—

	C	N	H
Per cent. . . .	56·0	5·36	5·1

It had a C/N ratio of about 10, as in the whole soil organic matter.

In recent years considerable information has been obtained by studying the changes that occur when plant residues are added to the soil. These changes are dealt with later (p. 406): the easily decomposable carbohydrates and proteins are rapidly attacked by soil micro-organisms, but other constituents are much more resistant. Lignin is one of the chief of these and it is therefore now regarded as the basis of humus. This view had already been put forward by Hébert and Dehérain (p. 200); in recent times it was first seriously studied by F. Fischer and H. Schrader.[3]

[1] C. W. B. Arnold and H. J. Page, *J. Agric. Sci.*, 1930, **20**, 460.

[2] R. P. Hobson and H. J. Page, *ibid.*, 1932, **22**, 296 and 497. For an older analysis see C. A. Morrow and R. A. Gortner, *Soil Sci.*, 1917, **3**, 297, who analysed the organic matter from a number of soils, and found that it was generally of the same type whatever the soil, but different from the organic matter of peat. A. A. Shmuk (*J. Exptl. Agron.* (Russian), 1914, **15**, 139) considered that 60-70 per cent. of the soil nitrogen is protein in character, while N. P. Remezov and K. V. Verigina (*Ztschr. Pflanz. Düng.*, 1934, A, **36**, 37) have studied the products of hydrolysis of the various types of soil in Russia.

[3] *Brennstoff-Chem.*, 1921, **2**, 37; see also H. Schrader, *ibid.*, 1922, **3**, 161.

Although lignin is resistant to the attack of micro-organisms it is not undecomposable: it slowly breaks down. Soil humus is, however, based on modified lignin, not on lignin itself; it contains a lower proportion of methoxyl groups, is more soluble in dilute alkali, and is darker in colour than lignin, and more readily oxidised.[1] In addition it is definitely though not very strongly acid; and it contains protein groups.

No drastic change in the lignin molecule would be necessary in order to account for these properties. Lignin, although not easily attacked by micro-organisms, has strong powers of combination with other substances. In the growing plant it is largely combined with hemi-celluloses [2] which in the soil are rapidly decomposed by micro-organisms leaving the lignin free: it partially oxidises with great ease and, as Page and Hobson [3] showed, in this state it readily unites with egg albumen to form a very stable combination.

This altered-lignin-protein complex is regarded by Page as the essential constituent of humus. It is soluble in dilute alkali and precipitated by acid: and in general it corresponds with the humic acid of the older workers.

Quite independently, Waksman put forward the same view, but gave more detail as to the mechanism of production. Like Page, he regards lignin as the basis of humus, and he showed that when dissolved in alkali it unites strongly with protein. When calcium, magnesium, iron and other metallic compounds are added to the solution and the whole precipitated by bringing the mixture to a *p*H of about 7, he obtained what he calls a humus-nucleus, which he regards as identical with soil humus.[4] He discusses the part played by micro-

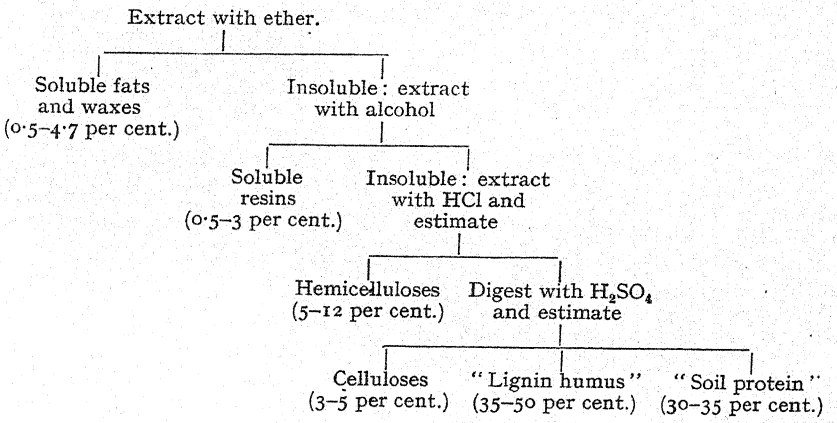
[1] I. D. Sedletsky and B. K. Brunovsky have shown by X-ray spectrographs a close genetic relationship in the series: lignin—humic acids—brown coal (lignite)—anthracite—graphite (*Trans. Int. Soc. Soil Sci.*, Soviet Section, Vol. A, 1935, p. 91).

[2] A. G. Norman and J. G. Shrikhande, *Biochem. J.*, 1935, **29**, 2259.

[3] R. P. Hobson, Thesis, Lond. Univ., 1926; *J. Agric. Sci.*, 1932, **22**, 497.

[4] S. A. Waksman and K. R. N. Iyer, *J. Wash. Acad. Sci.*, 1932, **22**, 41. Waksman summarised his views in *Trans. II. Comm. Int. Soc. Soil Sci.*, 1933, A, p. 119, and in his recent book *Humus*, 1936.

organisms and argues that during the decomposition of the plant residues some at any rate of the organic matter is built up into their tissues and these new substances, especially the proteins, react with the modified lignin to form humus. Waksman and K. R. Stevens suggest the following method of fractionating the organic matter :—[1]



They thus account for some 90 to 95 per cent. of the carbon in the soil. With further decomposition of the lignin portion of the complex it might be expected that a different type of humus would arise. U. Springer[2] distinguishes two types. A "Cassel brown" type was obtained from acid soils or from others of little humification, and this he regards as derived mainly from lignin. But from strongly humified soils he obtained a "black earth" type probably derived from more drastically altered material of higher molecular weight.

General Properties of the Humus.

We are here using the word humus in the sense of the organic matter of the soil after removal of fragments of undecomposed plants. Humus possesses many colloidal properties, but they have been less studied than those of clay, because there is no means of separating humus from the

[1] *Soil Sci.*, 1930, **30**, 97. [2] *Ztschr. Pflanz. Düng.*, 1934, A, **34**, 1.

soil that is in any way comparable in ease with the removal of the clay. So far the only practical method necessitates converting it into the sodium humus, in which form it is much more highly dispersed than the clay. N. B. Vernander and A. N. Sokolovsky [1] separated out the black clay and humus fraction from a chernozem by first removing the exchangeable calcium by *N* NaCl solution, then sedimenting the soil several times to remove the fraction greater than 1μ diameter. The dark-coloured suspension was then passed through a Berkefeld filter. At first it went easily, but as the pores became blocked up the passage was slower: a series of fractions was thus obtained, each with a definite rate of filtration and degree of dispersion. The unfiltered material contained 64 per cent. of ash; the final fraction 2 per cent. only.

In view of this difficulty of separation recourse has frequently to be had to indirect methods and to statistical methods for studying the properties of humus.

Acid Properties.

Several investigators have calculated combining or equivalent weights for humic acid, but as the methods and assumptions have not always been the same the values are not strictly comparable. Some of the figures are—

Odén . . .	340	*Koll. Chem. Beit.*, 1919, **11**, 75.
Hissink . . .	155 to 194; Av. 176	*Trans. Second Comm. Int. Soc. Soil Sci.*, 1926, A, 198.
G. Thiessen and C. J. Engelder . .	800 [2]	*Ind. Eng. Chem.*, 1930, **22**, 1131.
L. Kotzmann . .	309	*Mezö. Kutatások*, 1929, **2**, 537.
P. E. Turner . .	660 (Tropical soils) 710 (Dutch sandy soils) [3]	*J. Agric. Sci.*, 1932, **22**, 72.
S. Mattson . .	326; 350	*Soil Sci.*, 1931, **31**, 57.

[1] *Proc. 1st Int. Cong. Soil Sci.*, Washington, 1928, **3**, 367.

[2] Molecular weight. [3] Calculated from Hissink's analyses.

Odén's and Hissink's figures are not comparable with the rest: Odén's figure is for "humic acid" (fraction 9, p. 199), not for the whole humus complex. Hissink's figures refer to the whole humus complex in humus soils poor in clay. The conditions of determination of the total amount of bases absorbable differ from those adopted by other workers. Turner, applying his method to Hissink's data, obtained the figure 710, which compares with his own of 660. Either method shows that the humus colloid is about six or seven times as potent an absorber as the clay colloid :—

	Equivalent Weights.		Ratio.
	Humus.	Clay.	
Hissink	176	1225	1 : 7
Turner	660	4100	1 : 6·2

Base Exchange.—In general the base exchange phenomena resemble those shown by clay, but they have been less investigated, and no clear picture of the process has been put forward. McGeorge [1] found so close a relationship between the total exchange capacity and the carbon content of the soils examined, as to make it appear that the humus overpowered the effect of the clay. For each 10 grm. of carbon in the soil the exchange capacity increased by 35 mg.-equivalents (Fig. 25), which gives a value of 240 mg.-equivalents per 100 grm. of humus colloid. For "humic acid," prepared as on page 199, he obtained the value 370. He further showed that the total exchange capacity of the organic matter was closely related to the lignin carbon, and not to the carbon associated with the hemicelluloses or celluloses.

P. E. Turner,[2] working with a large number (56) of tropical soils, was able to evaluate the exchange capacities both of

[1] W. T. McGeorge, *Ariz. Agric. Expt. Sta. Tech. Bull.* No. 30, 1930.
[2] *J. Agric. Sci.*, 1932, **22**, 72.

the organic matter and of the clay. He assumes the absorption to be an additive effect, *i.e.* that the absorption of the humus is not greatly affected by the presence of clay: he then expresses the total saturation capacity as

$$\alpha + \beta x_1 + \gamma x_2$$

where α, β, and γ are constants depending on the soil type, x_1 is the quantity of organic matter, and x_2 of clay. The value for organic matter was 151 mg.-equivalents per 100 grms., while that for clay was only 24,[1] *i.e.* only about one-seventh

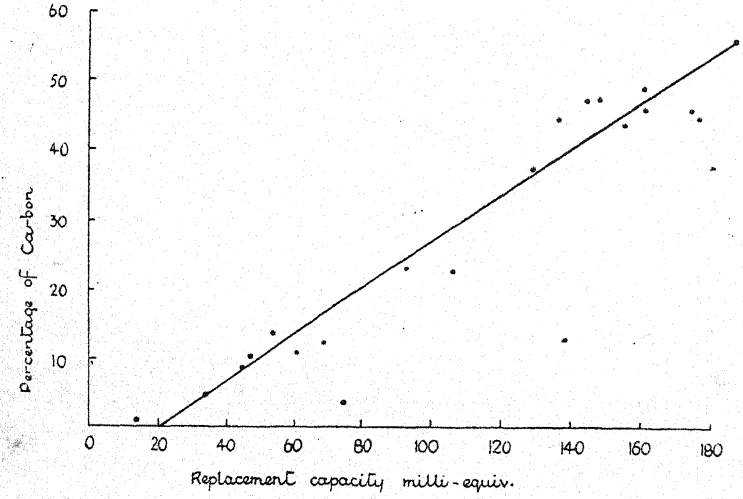


FIG. 25.—Relation between the total replacement capacity and the percentage of carbon in soil (W. T. McGeorge).

as much. By the same method of calculation he obtained 140 for the organic matter of the sandy humus soils of Holland, using Hissink's analytical data.

Association of Clay with Humus.—This high capacity for absorbing cations is not the only combining power possessed by humus: it also readily unites with clay, though the mechanism of the combination is not known. The phenomena

[1] Reference to p. 184 shows that this clay value is comparable with those of low SiO_2/Al_2O_3 ratio such as one might expect to find under tropical conditions.

have long been observed. "L'argile," wrote Th. Schloesing in 1874,[1] "possède une certaine tendance à s'unir aux humates du terreau pour former probablement une de ces combinaisons entre colloides signalées par Graham." He attempted a separation by suspending in ammonia solution, then adding ammonium chloride: this precipitated the clay but not the humus. He found, however, that the quantity of chloride required to flocculate the clay increased with the amount of humus present and might rise to 20 grms. per litre of suspension. This observation that clay does not flocculate so readily in presence of humus as in its absence, was first fully investigated by E. Fickendey.[2] Ehrenberg[3] supposes two stages:—

(1) The aggregated clay particles are peptised or dispersed by the humus;

(2) The clay particles thus become coated with absorbed humus, so that they behave as if they were humus and not clay.

A. Demolon and G. Barbier[4] showed that while a humus suspension tended to stabilise a clay suspension, as would be expected for a mixture of two sets of particles of the same electrical sign, addition of a clay suspension to a humus suspension tended to sensitise it, so that it became more easily flocculated on addition of electrolyte. They showed that humus and clay came down together, but that the amount of humus fixed by the clay increased as the *p*H fell: they studied also the effect of the calcium ion.

Dispersion.—Humus is so completely dispersible in solutions of sodium, potassium, and ammonium hydroxides as to form almost a solution; it is filterable through a fine ultrafilter, yet it always shows the Tyndall ray effect. Successive fractions obtained by Vernander and Sokolovsky contained less and less carbon and nitrogen, and more hydrogen and oxygen, suggesting that the finest material is more hydrated

[1] *C.R.*, 1874, **78**, 1276.
[2] *J. Landw.*, 1906, **54**, 343.
[3] *Die Bodenkolloide*, 2nd edn., 1918.
[4] *C.R.*, 1929, **188**, 654.

than the coarser ; [1] the percentage composition of the organic matter in each was—

Fraction.	C Per Cent.	H Per Cent.	O Per Cent.	N Per Cent.
Original	56·5	5·7	34·4	4·25
1st filtrate (coarse) . .	—	—	—	4·18
4th ,, (finer) . .	—	—	—	3·7
9th ,, (finest) . .	36·7	7·2	52·6	3·5

The properties of alkali humus dispersions show some resemblance to those of soap and of Congo red.[2]

Calcium humus is much less readily dispersed than the associations with hydrogen, ammonium, or sodium.

Flocculation.—The flocculation of humus suspensions was studied by Odén : he used humic acid extracted from peat, and showed that its particles when suspended in water are negatively charged and range about 0·020μ diameter and can be flocculated in the same way as clay but require larger quantities of electrolyte ; calcium salts are particularly effective.

In absence of evidence to the contrary, and in view of the general similarity in flocculation phenomena, the systems humus-water and clay-water may be regarded as similar, the humus micelle being large and complex, capable of base exchange, and surrounded by an electric double layer, like that of clay.

S. Mattson [3] has studied the isoelectric humates of aluminium, iron, etc., obtained by precipitating a suspension of sodium humate with solutions of metallic chlorides.

[1] The original carbohydrate material of the plant contains about 40 per cent. of carbon ; the soil humic matter is much dehydrated and contains 58 per cent. Humic acid (fraction 9, p. 199) is more dehydrated and contains 60 to 62 per cent. This finest material is much less dehydrated and contains 37 per cent.

[2] J. W. McBain, *Brit. Assoc. Third Rept. Coll. Chem.*, 1920, p. 2 ; B. A. Riazanov, *J. Landw. Wiss.*, Moscow, 1927, **4**, 697 ; G. Stadnikov and P. Korshev, *Koll. Ztschr.*, 1929, **47**, 136.

[3] *Soil Sci.*, 1931, **31**, 57.

Effects of Humus on the Fertility of the Soil.

There is no direct method of discovering the effects of humus on soil fertility, but the statistical methods introduced in recent years into agricultural science promise to be very useful.

The main effects produced are set out below.

(1) It gives a dark brown or black colour to the soil unless much calcium carbonate is present when the colour may be masked.

(2) It increases the retentive power of the soil for dissolved substances, thus acting like clay.

(3) In presence of calcium carbonate or of sufficient exchangeable calcium it does not wash down in the soil but remains fixed in the surface. In absence of sufficient calcium, however, it becomes dispersed and washes down to a certain depth.

(4) It causes the soil to become puffed up, and so leads to an increase in the pore space (see p. 484). From this results a marked improvement in the tilth and general mechanical condition. The Rothamsted mangold plots receiving no organic manure, and therefore poor in partially decomposed organic matter, get into so sticky and "unkindly" a state that the young plants have some difficulty in surviving, however much food is supplied, and may fail altogether in a dry spring; the dunged plots rich in humus are much more favourable to the plant and never fail to give a crop. But the puffing up or "lightening" may go too far, and sometimes causes much trouble in old gardens that have long been heavily dunged.

(5) It increases the water-holding capacity of the soil. The amounts of moisture present in adjacent plots at Rothamsted are shown in Fig. 26, from which it appears that the plot annually receiving farmyard manure contains normally 3 or 4 per cent. more water than the adjoining plot receiving no organic manure. The variations in water content of similar

pairs of soils follow closely the differences in the amounts of organic matter present.

So marked are these physical effects that if 15 or 20 per

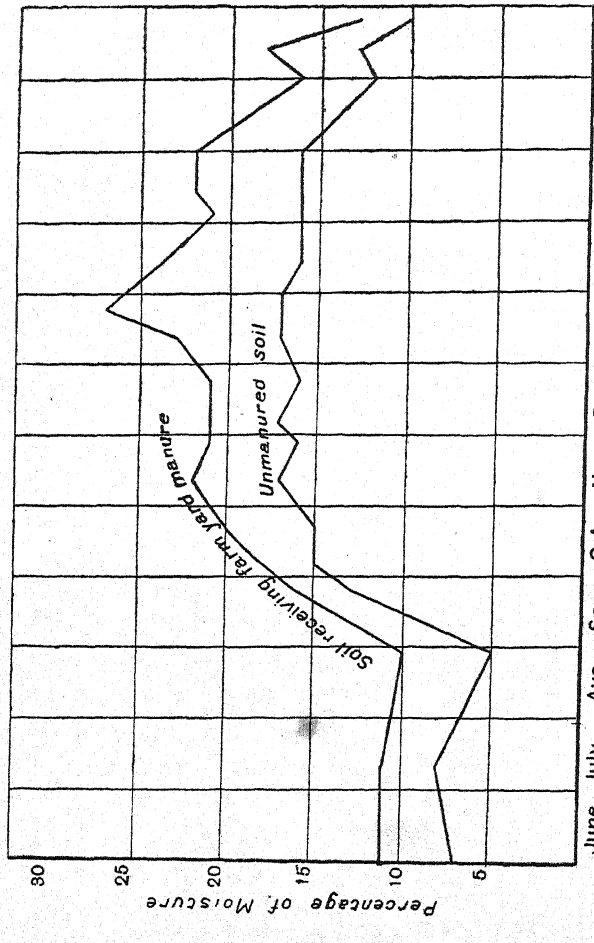


FIG. 26.—Curves showing the percentage of water in two soils on adjacent plots, one of which annually receives farmyard manure while the other does not (Broadbalk field, Rothamsted).[1]

cent. of organic matter is present in a soil, the operation of other factors ceases to count for much, and the distinctions between sands, loams, and clays tend to be obliterated.

[1] E. J. Russell and A. Appleyard, *J. Agric. Sci.*, 1915, 7, 1.

(6) It swells when wetted. Peat shows this phenomenon in a marked degree ; indeed, after heavy rainfall inadequately drained peat bogs may swell so much as to overflow into valleys with disastrous results. After drainage, however, drying and shrinkage set in, followed by a slow but steady decomposition as air penetrates into the newly-formed pore spaces and starts the oxidation processes. When Whittlesey Mere was drained, a pillar was driven in 1850 through the peat into the underlying gault, and the top of the pillar was made flush with the surface of the soil. So great has been the subsequent shrinkage that nearly 11 feet of the pillar are now out of the ground.[1] The local inhabitants think that this amount of shrinkage has been general in the district. The Ordnance Survey have no data before 1886, nor after 1924: between these dates, however, the levels do not seem to have changed.[2]

(7) Although humus is essentially transitional it has a certain degree of permanence and only slowly disappears from the soil; at Maiden Castle in Dorset a layer of soil buried under chalk over 2,000 years ago is still visible as a dark band. It disappears more rapidly from chalky and sandy soils than from loams and clays.

(8) It increases the biological activities going on in the soil.

These properties greatly enhance the fertility of the soil, and in most schemes of husbandry definite arrangements are made to keep up or even increase the supply of organic matter while in forests the removal of leaves and other decomposable material is recognised as undesirable.

Němec [3] of Prague, studying the forests of Czechoslovakia, found that the removal of the litter lowered the nitrogen content of the soil, and this in turn lowered the nitrogen

[1] See Gordon Fowler, *Geogr. J.*, 1933, **81**, 149.

[2] For further information see S. H. Miller and S. B. J. Skertchly's, *The Fenland, Past and Present*, 1878, pp. 162-165.

[3] *Forstarch.*, 1929, **24**, 497 ; *Forstwiss. Cbl.*, 1931, **53**, 49 and 147.

content of the leaves by an amount averaging 12·2 per cent. and the annual growth increment of the trees by amounts which varied up to 40 per cent. Eight forests were studied, and the average percentage reduction in soil nitrogen content was—

Depth of Soil Layer, cm.	Percentage Reduction of Nitrogen Content in the Cleared Soils.	
	Total N.	Soluble N.
0–2	58·6	39·9
2–5	60·2	41·7
5–10	32·8	23·4
10–25	15·0	22·9

He also showed that removal of humus usually increases the proportion of silica, and sometimes of potash, in the leaf ash, while decreasing all other minerals and nitrogen. Further, it alters the air, water, and other biological conditions of the soil, usually unfavourably. It may be justified on very acid soils where there is a great accumulation of raw humus, or where cleaning the forest floor is needed to facilitate natural regeneration.

Burning the humus *in situ* is rather a different matter; it liberates plant nutrients, and stimulates nitrification. In Sweden it is sometimes essential before natural regeneration can be obtained.[1]

The Constitution of the Soil.

The colloidal properties of the soil are largely determined by the clay and the organic matter, but are not necessarily proportional to the amounts of these materials. Many years ago, J. Dumont [2] put forward the view that all the mineral particles of the soil are coated with a colloidal layer and therefore all have to that extent colloidal properties. This

[1] See H. Hesselman, *Medd. Skogsförsöksanst.*, 1917, **14**, 923.
[2] *C.R.*, 1909, **149**, 1087.

view finds some support from the fact that when a soil is "cleaned" by treatment with various weak reagents, its colloidal properties are reduced, but if only little organic matter be present, the "clean" clay accounts for practically all the base exchange capacity and other properties of the "clean" soil.[1] There is as yet no method for estimating directly the effect of the organic matter, though this must often be great; for equal weights it is greater than that of the clay; all that can be done is to make numerous quantitative measurements and then attempt to evaluate the effects of the clay, the organic matter, and the rest of the soil constituents. The simplest assumption is that the effects are additive: this was adopted by Turner (p. 216), but the flocculation phenomena show that there may be some interaction between the clay and the humus.

Chemical Properties of the Soil.

The chemical properties of the soil are mainly due to the clay, the organic matter, and the calcium carbonate present.

Soil Acidity.

*p*H *Value.*—The properties of the soil acids have already been discussed (pp. 154-159). One of the most important from the point of view of plant growth is the intensity of the acidity, *i.e.* the hydrogen-ion concentration in the neighbourhood of the soil particles, which is usually expressed as its negative logarithm or *p*H. It is measured for field work by some simple colorimetric test, and for more accurate laboratory investigations by the platinum or glass electrode or the simpler quinhydrone electrode where this is practicable.[2] Unfortunately it cannot be measured *in situ* except in wet soils; generally a sample of the soil must be shaken up in water or other solution and the *p*H of this measured.

[1] R. H. J. Roborgh, *Thesis*, Wageningen, 1935.

[2] *E.g.* in absence of manganese dioxide (S. G. Heintze and E. M. Crowther, *Trans. II. Comm. Int. Soc. Soil Sci.*, Budapest, 1929, A, p. 102), and where the *p*H value does not rise above 8.

Air drying and storing of the soil do not appear much to affect its *p*H; they commonly reduce it by some 0·2 of a *p*H unit,[1] though Aarnio reports differences up to 1·2 *p*H units for some soils.

The recorded limits for the *p*H of soils are 9·6 (found by L. T. Sharp and D. R. Hoagland)[1] to 2·2 (found by H. L. Jensen in Denmark).[2] A solution saturated with carbon dioxide at its normal partial pressure in the air in the presence of calcium carbonate has a *p*H of 8·4.

Table 39 gives some idea of the proportion of soils whose *p*H lies within a given range for several countries.

TABLE 39.—PERCENTAGE DISTRIBUTION OF THE *p*H VALUES OF SOILS IN DIFFERENT COUNTRIES. O. ARRHENIUS.[3]

Country.	No. of Samples.	*p*H lying between										
		4·0-4·5.	4·5-5·0.	5·0-5·5.	5·5-6·0.	6·0-6·5.	6·5-7·0.	7·0-7·5.	7·5-8·0.	8·0-8·5.	8·5-9·0.	above 9·0
Japan . .	27	—	19	19	15	23	19	5	—	—	—	—
Finland .	—	1	8	23	38	21	8	1	—	—	—	—
S.E. Scotland[4]	4000	1	3	19	39	21	10	5	2	—	—	—
Denmark .	5000	—	1	3	12	46	21	14	2	—	—	—
Sweden .	5000	1	2	5	10	25	31	24	2	0·03	—	—
Java . .	73	—	—	—	—	—	14	57	26	3	—	—
Egypt .	56	—	—	—	—	—	—	14	48	22	—	16

TITRATION OR BUFFER CURVES AND LIME REQUIREMENTS OF SOILS.

In practical soil management it is important to know the amount of base or acid that must be added to a soil to bring its *p*H to any selected value. Lime is the base that has been most extensively investigated. Figs. 27 and 28 show the titration curves obtained by shaking soil with increasing quantities of lime and determining the *p*H by the hydrogen

[1] *J. Agric. Res.*, 1916, **7**, 123.
[2] *Zbl. Bakt.*, Abt. II, 1927, **72**, 242.
[3] *4th Int. Conf. Pedology*, Rome, 1926, **2**, 502.
[4] W. G. Ogg, private communication.

electrode. In Fig. 27, two soils, Woburn and Harpenden Common, start at about the same *p*H, but they require different amounts of lime to bring them to *p*H 7. The Woburn soil requires only little; it is a sandy soil without much clay or organic matter and is therefore only lightly

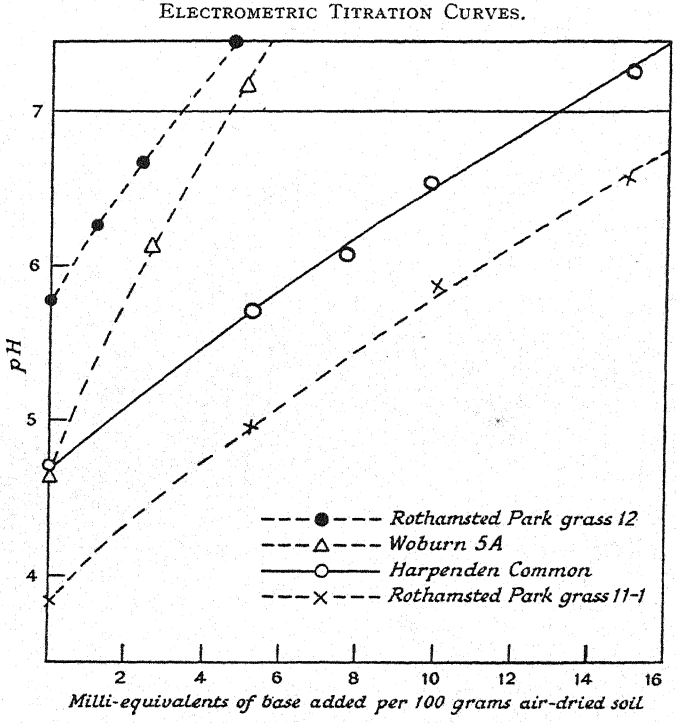


FIG. 27.—Changes in reaction (*p*H) of acid soils with successive additions of lime water (E. M. Crowther and W. S. Martin, *J. Agric. Sci.*, 1925, 15, 237).

buffered; while the Harpenden Common soil containing a larger amount of clay and organic matter requires more lime and is the more heavily buffered. Unfortunately these laboratory results cannot be converted into field units without using some empirical factor. In the laboratory a certain weight of soil is allowed to come into equilibrium

with a solution containing lime of known strength, while in the field a certain quantity of lime is added to a known surface area of soil. H. R. Christensen and S. Tovborg Jensen [1] determined the titration curves in the laboratory of soils from a number of plots in various parts of Denmark to which successive increasing doses of lime had been added. They converted their laboratory results to hypothetical field results assuming that the top 20 cm. of soil weighed 2·4 million kg.

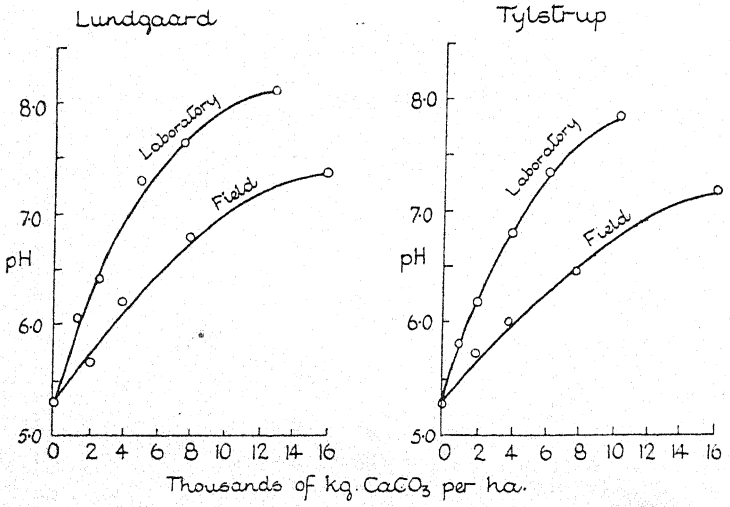


FIG. 28.—Influence of successive additions of $CaCO_3$ on the *p*H values of two acid soils in the laboratory and the field respectively (H. R. Christensen and S. Tovborg Jensen, *Trans. II. Comm. Int. Soc. Soil Sci.*, Groningen, 1926, A, p. 94).

per ha. and absorbed and retained the whole of the added lime (Fig. 28). These estimated values were, however, only about one-third of those actually required in the field to effect the same change in reaction. For the present the cause of the discrepancy is not fully understood, though leaching into the subsoil probably accounts for much of the loss.

For many purposes the whole titration curve is not required, but only the amount of lime needed to raise the *p*H up to a given level. Before *p*H measurements were introduced it was

[1] *Trans. II. Comm. Int. Soc. Soil Sci.*, Groningen, 1926, A, p. 94.

customary to estimate by some empirical method the "lime requirement" of soils, this being the amount of lime in hundredweights per acre that must be added to a "sour" soil to make it neutral or "sweet." In England, H. B. Hutchinson and K. MacLennan's [1] method has been most frequently used; the soil is shaken with a calcium bicarbonate solution, and the amount of calcium absorbed is taken as a measure of the lime requirement.[2]

*p*H measurements and titration curves have now largely displaced the "lime requirement" methods. A determination is made of the amount of base that a soil must hold in order to have a selected *p*H; soil holding that amount is said to be "saturated" up to that *p*H under the conditions of measurement, and the amount of base then held is often called its "saturation capacity."

There has been much discussion as to the most useful *p*H for agricultural purposes. An upper limit is obviously set by the amount of lime a soil can hold when it is in equilibrium with calcium carbonate at the partial pressure of carbon dioxide existing in the soil air and soil solution; this corresponds to a *p*H of between 8·3-8·4 under normal humid conditions.[3] But this quantity is unnecessarily high, and for many plants a lower *p*H suffices (p. 535).

The Amphoteric Properties of Soils and Clays.

Absorption of Anions by Soils.

All soils and clays can absorb the phosphate ion under certain conditions, and some can absorb sulphates and

[1] *J. Agric. Sci.*, 1915, **7**, 75. H. Kappen used neutral calcium acetate, *Die Bodenazidität*, Berlin, 1929.

[2] E. M. Crowther and W. S. Martin (*J. Agric. Sci.*, 1925, **15**, 237) showed that the final *p*H to which the soil is brought by this method is very variable, ranging from *p*H 6·1 to 7·0. R. K. Schofield, *J. Agric. Sci.*, 1933, **23**, 252, uses a solution of *p*-nitrophenol half neutralised with lime which is strongly buffered at *p*H 7·0.

[3] R. Bradfield and W. B. Allison (*Trans. II. Comm. Int. Soc. Soil Sci.*, Copenhagen, 1933, A, p. 63) gave methods for the experimental determination of this quantity.

chlorides. The mechanism of these absorptions is not known, and it is not possible to say how far the soil can behave as an amphoteric system (p. 158).[1]

Owing to its technical importance the absorption of the phosphate ion has been much studied. P. L. Gile has investigated it in pot experiments to find the effect of various treatments on the loss of availability of added superphosphate,[2] while numerous investigators have made laboratory studies. The results show considerable variation according to the soils and the conditions of experiment, and it is clear that the phenomena are very complex. At least three types of absorption have been described: simple precipitation on ordinary chemical lines; absorption of the anion; and absorption of the entire molecule. Several of the soil constituents take part. The clay fraction is largely concerned, and of its various components the iron and aluminium oxides have been much studied. Calcium carbonate when present plays an important part, as also does the organic matter.

Gile grew plants in sand containing quantities of soil supplying a constant amount of colloid, and found that the effectiveness of added superphosphate was greatly reduced by the soils least saturated with P_2O_5, and by those with colloids of low SiO_2/R_2O_3 ratios (*i.e.* below 2): for these the reduction appeared to be more pronounced at higher than at lower *p*H values, but the data are few. The organic matter seemed to play a less important part. The Rothamsted field experiments long ago showed that additions of sodium silicate to the barley crop had similar effects to small additions of superphosphate, and this result has been interpreted as showing that soluble silica increases the availability of the phosphate, which is in accordance with the above observations.

[1] For a discussion see a series of papers by S. Mattson, *Soil Sci.*, 1932, **34**, 209; *J. Amer. Soc. Agron.*, 1926, **18**, 458 and 510; *Soil Sci.*, 1929, **28**, 179; *Proc. 1st Int. Cong. Soil Sci.*, Washington, 1928, **2**, 199.

[2] P. L. Gile, *U.S.D.A. Tech. Bull.* No. 371, 1933.

The laboratory investigations accord in general with these vegetation results. The phenomena are expressible by the Freundlich equation,[1] and to this extent resemble many other absorptions. Soils have no definite power of fixing phosphate : the amount fixed depends on the amount supplied, and the larger the amount added the less firmly is it held against the solvent action of water. In other directions the absorption of phosphate by soil differs from ordinary absorptions ; it is not instantaneous but may continue for a long time.[2]

The phenomena differ according as the soils are acid or neutral.

In acid conditions the iron and aluminium oxides play an important part, and different soils vary in their absorptive power according to the amounts of these substances present in an easily soluble form.[3] For a given soil the absorbing power is decreased by removing them, though the decrease is not proportional to the amount of iron removed.[4] Combined silica has the reverse effect, and under constant *p*H reaction of the medium the absorption of phosphate increases as the

[1] E. J. Russell and J. A. Prescott, *J. Agric. Sci.*, 1916, **8**, 65.

[2] P. L. Hibbard, *Soil Sci.*, 1935, **39**, 337 ; L. E. Davis, *Soil Sci.*, 1935, **40**, 129. G. D. Scarseth and J. W. Tidmore, however, found that the reaction between $-PO_4$ and colloidal clay was practically instantaneous, while for soils it continued much longer (*J. Amer. Soc. Agron.*, 1934, **26**, 138 and 152 ; and L. E. Davis, *loc. cit.*).

[3] I. N. Antipov-Karataev and A. I. Rabinerson (*2nd Int. Cong. Soil Sci.*, Moscow, 1933, **2**, 108). The solvent was Tamm's acid oxalate solution.

[4] L. A. Dean, private communication. Some of the results are as follows :—

Parts per million of phosphorus fixed before and after soils were treated with H_2S by the Truog method :—

Soils from	Before Treatment.	After Treatment.	Per Cent. Fe_2O_3 Removed.
Connecticut . .	140	130	2·7
Wisconsin . .	205	130	2·9
Hawaii 1 . . .	450	420	18·0
,, 2 . . .	345	200	10·5

SiO_2/R_2O_3 ratio decreases, so long as one keeps within the usual *p*H range of soils.[1]

The relation between absorption and *p*H of the medium varies according to the conditions: in general, working with the colloidal clay fraction, and starting from near neutrality, absorption increases as the *p*H of solution falls off. The maxima and minima vary according to the other ions present. The changes in the form of the curve with changes in the proportions of basoid or acidoid components in the soil have been studied by T. Gaarder and O. Grahl-Nielsen.[2]

The phosphate absorbed in acid conditions is so firmly held that it is not easily recovered from the soil either by the plant or by weak acids. It is, however, replaceable by the —OH or the silicate ion: Scarseth was able to obtain on an acid clay as good a response to sodium silicate as to phosphate fertiliser.

In neutral conditions the iron and aluminium oxides apparently play a less important part and precipitation is on the calcium, but it may take two forms: a somewhat soluble combination easily available to growing plants where the calcium is present in relatively small quantities, and a less soluble and less available form, possibly a carbonate-apatite, where it is present in excess.[3]

Demolon [4] and Bastisse showed that the absorption of the phosphate ion is affected by the presence of other anions; less phosphate was absorbed from a mixture of phosphate with another absorbable anion (*e.g.* tartrate, citrate, oxalate, and silicate) than from a mixture with a non-absorbable anion

[1] S. Mattson, *Soil Sci.*, 1931, **32**, 343. Four electrodialysed soil colloids and a bentonite were used.

[2] *Medd. Vestlandets Forst. Forsøksstat.*, 1935, No. 18.

[3] T. Gaarder, *ibid.*, 1930, No. 14 (in German). See also W. T. McGeorge and J. F. Breazeale, *Ariz. Agric. Expt. Sta. Tech. Bull.* No. 40, 1932.

H. R. Christensen (*Tidskr. for Planteavl*, 1922, **28**, 1) found that a solution of CO_2 in water extracted much more PO_4 from neutral soil than from acid soils. The subject was studied by M. von Wrangell and her colleagues: see, for example, M. von Wrangell and W. Haase, *Landw. Jahrb.*, 1926, **63**, 707.

[4] A. Demolon and E. Bastisse, *Ann. Agron.*, n.s., 1934, **4**, 53.

(*e.g.* Cl, SO_4, NO_3). Further, phosphate fixed by the soil could be removed more easily by a salt of an absorbable than of a non-absorbable ion.

The fact that removal of easily soluble alumina and iron decreases the phosphate absorption, and as already shown (p. 153) increases the cationic exchange, suggests that absorption of anions is not brought about by the same surfaces as absorb the cations. Mattson [1] pictures the clay surface as containing ionisable —OH and H ions which can dissociate simultaneously, though the hydroxyl ion dissociation predominates in acid conditions and the hydrogen ion dissociation in alkaline conditions. He assumes that lateritic soils contain a high proportion of ionisable hydroxyl ions and bentonite soils a low proportion.

Humus also appears to have but little power of absorbing phosphate; indeed soluble humates prepared from brown coal prevent the precipitation of phosphates by calcium salts over a wide range of *p*H values. Humus may thus assist in transporting phosphorus to lower depths in the soil.[2]

Another amphoteric property that has been much studied is the ease with which the soil can be turned from an electronegative to an electropositive colloid by addition of hydrochloric acid. This also is said by Mattson to become more pronounced as the SiO_2/R_2O_3 ratio of the clay decreases, though Antipov-Karataev claims that it is only the easily soluble, and not the total, sesquioxide that counts.

Retention of Colloids by the Soil Colloids.—This has been studied chiefly for dyes, and the subject at one time attracted much interest because it afforded a method for estimating the amount of colloidal material in the soil.[3] This absorption is now regarded, however, as a base exchange, for it is

[1] S. Mattson, "The Laws of Soil Colloidal Behaviour" (series in *Soil Sci.*) and papers in the new journal *Lantbr. Högsk. Ann.*

[2] T. Gaarder and O. Grahl-Nielsen, *loc. cit.*; J. L. Doughty, *Soil Sci.*, 1935, **40**, 191; O. Flieg, *Ztschr. Pflanz. Düng.*, 1935, A, **38**, 222.

[3] For the older literature see a discussion by J. A. Hanley, *J. Agric. Sci.*, 1914, **6**, 58.

apparently only the basic dyes that are absorbed: the anions of acid dyes are not.[1]

Other absorptions of colloids may prove to be no more than base exchanges or precipitations: in the meantime we can describe them as retentions without expressing any view as to how they are effected.

The retention of humus by clay is one of the most important factors in soil fertility. It has a marked influence on flocculation, soil texture, and pan formation (pp. 207, 209, 275). A further important consequence is to keep added organic matter, whether coming from farmyard manure

TABLE 40.—NITROGEN IN BROADBALK WHEAT SOILS, 1893.

Per cent. of dry soil.

	Annual Dressing of Manure.					
	Unmanured.	Dung (200 lb. N).	Minerals only.	Minerals + 200 lb. Ammonium Salts (43 lb. N).	Minerals + 400 lb. Ammonium Salts (86 lb. N).	Minerals + 600 lb. Ammonium Salts (129 lb. N).
Top 9 ins. .	·0992	·2207	·1013	·1107	·1222	·1188
9 to 18 ins. .	·0730	·0767	·0739	·0720	·0681	·0752
18 to 27 ins. .	·0651	·0656	·0645	·0628	·0583	·0630
Lb. per acre.						
Top 9 ins. .	2572	5150	2630	2870	3170	3080
9 to 18 ins. .	1950	2050	1970	1920	1820	2010
18 to 27 ins. .	1820	1830	1800	1750	1630	1760
Nitrogen supplied in manure in the 50 yrs.	None	10,000	None	2150	4300	6450

[1] J. A. Wilkinson and W. Hoff, *J. Phys. Chem.*, 1925, **29**, 808; also J. G. Smith and P. L. Gile, *J. Agric. Res.*, 1930, **41**, 401.

or vegetation, largely in the surface layers of the soil so long as sufficient calcium is present. Even when heavy dressings of dung are annually applied at Rothamsted, there is, after fifty years, no appreciable enrichment of the subsoil in nitrogen (Table 40). The purification of sewage by land treatment affords further illustrations of the absorptive power of soil for organic matter. In English experience a sewage farm on a good loam can deal with 30,000 to 40,000 gallons of sewage per acre per day (*i.e.* 1·3 to 1·8 inches per day).

The Absorption of Gases and Liquids by Soils and Clays.

Soils possess to a marked degree the property of absorbing gases, vapours, and liquids.

Air, nitrogen, and oxygen are all equally absorbed (about 0·1 cc. per gram of soil under ordinary conditions); they are held so firmly that the absorbed gas is not all removed by a simple evacuation, though it can be displaced by water either as vapour or liquid. The power of absorption decreases as the moisture content of the soil rises.[1]

Ammonia gas is more strongly absorbed than carbon dioxide, probably because it interacts with the hydrogen ions of the clay and humus.

Liquids can apparently be absorbed in two ways.

(1) They may condense between the soil particles or in the fine capillaries of the soil crumbs as pictured by the capillary condensation hypothesis of Zsigmondy and Patrick: Schofield has shown that most of the soil water is probably held like this.

(2) If their molecules are polar they may be orientated around the ions of the clay and so immobilised as pictured by E. W. Russell (p. 191). The amount of liquid thus absorbed is estimated from the variation in specific gravity of the same soil or clay in different liquids: for clays it is in the

[1] H. Wiessmann and W. Neumann, *Ztschr. Pflanz. Düng.*, 1935, A, 40, 49.

main proportional to the base exchange capacity of the clay and it increases with the surface density of charge on the exchangeable ions; the order of activity of the cations is Mg > Ca > Na > K. Absorption of this kind is most pronounced for water and the simple alcohols, less for nitrobenzene, and least for the non-polar liquids such as benzene or carbon tetrachloride.

The Density of a Soil.

One of the results of the absorption of liquids and gases by soils is that no accurate determination of the density of the soil can be made. The volume of a soil as estimated by the ordinary methods in a specific gravity bottle or pyknometer is too low because the soil absorbs some of the liquid; hence the density comes out too high.

A true value could be obtained only if the liquid properly wetted the soil and none of it was absorbed. The density of a soil as determined in a non-polar liquid such as toluene affords the best estimate at present obtainable.

Heat of Wetting of Dry Soils.—A dry soil immersed in water evolves heat, and the amount evolved is often taken as a measure of the colloidality of the soil or of the extent of its surface.[1] The heat of wetting both of clay colloids and of calcium-hydrogen soils is approximately proportional to their base exchange capacity.[2] The exchangeable ions held by the soil also affect its heat of wetting; soils saturated with exchangeable magnesium have the highest heat of wetting and others follow in the order: Mg > Ca > Na > K. Hydrogen or acid soils behave very like calcium soils. Janert [2] goes further and claims that the heat of wetting of a soil is a constant proportion of the heat of hydration of the exchangeable

[1] For an account and discussion see E. A. Mitscherlich, *Bodenkunde für Land- und Forstwirte*, 4th ed., P. Parey, Berlin, 1923.

[2] Parker and Pate for the colloids (see p. 185); Janert (*J. Agric. Sci.*, 1934, **24**, 136) for the soils. Janert measured the base exchange capacity by Schofield's potassium phosphate method (*J. Agric. Sci.*, 1933, **23**, 255).

ions, which is highest for sodium and potassium, lower for calcium and magnesium, and lowest for hydrogen.[1]

H. Janert and J. L. Russell [2] attempted to estimate the quantity of exchangeable hydrogen in a soil by determining its heat of wetting in water and in barium hydroxide and attributing the difference to the heat of neutralisation in the reaction $H^+ + OH^- = H_2O + 13{\cdot}8$ Cals.

Ignited soil has little or no heat of wetting unless it contains gibbsite ($Al_2O_3 . 3H_2O$) as, for example, the laterites, bauxites and lateritic earths (p. 311). Hardy [3] has suggested this might afford a means of estimating the quantity of gibbsite in a soil.

Swelling of Soils.

The heat of wetting and the increase in apparent specific gravity of soil are both related to the energy change involved when a dry soil is wetted. But a soil swells on wetting, and the volume changes do not follow the same rules as the energy changes. Experiments on the influence of the different soil properties, such as the base exchange capacity, the type of exchangeable ions held by the soil, and the silica-sesquioxide ratio of the clay, on the properties related to the swelling of the soil have given rather discordant results, possibly due to the great variability of technique employed. It appears, however, that soils of high exchange capacity swell more than soils of low exchange capacity when wetted with water; also that soils saturated with exchangeable sodium ions swell more than those holding potassium; calcium and hydrogen soils come intermediate in that order.[4]

[1] P. I. Andrianov (*J. de Phys. Techn.*, 1933, **3**, fasc. 7, quoted by I. N. Antipov-Karataev, *Trans. Int. Soc. Soil Sci.*, Soviet Section, 1935, A, p. 90) claims to have arrived at this same result.

[2] *Ztschr. Pflanz. Düng.*, 1934, A, **33**, 79. They attempted also to estimate the amount of organic matter by comparing the heats of wetting in water and in carbon tetrachloride, but here they were not uniformly successful.

[3] *Nature*, 1934, **134**, 326.

[4] L. D. Baver and H. Winterkorn, *Soil Sci.*, 1934, **38**, 291; 1935, **40**, 403.

Soil Structure.

It has been already shown (p. 190) that clay under certain conditions readily forms crumbs or granules[1]: humus also has the same property. When these conditions are applied to soils the silt and sand particles become caught up with the clay and the humus, and if sufficient of these be present the whole soil can take on a crumb structure. The crumbs can unite to form aggregates of various sizes. Three different types of structure are obtainable :—

(1) *On Light Soils.*—Particles mainly loose and separate, there being insufficient colloid to bind them. This type of structure is called " einzelkörnig " by the German workers.

(2) *On Heavy Soils.*—Crumbs, where the colloid suffices for binding and the conditions permit it. Each individual crumb contains all the soil constituents, and might in eighteenth-century language be described as a " perfect microcosm " of the soil.

The granules can combine to form the " nuts " of chernozems which resist small pressures, but are readily broken down on gentle tapping.

(3) At the other extreme the soil particles unite into hard steely lumps or clods which are broken only with difficulty. These extreme cases can be distinguished, but not the intermediate states.

[1] The Russian workers use the word " granular " to denote the most perfect development of structure. Soil granules somewhat resemble a wheat grain in size and shape, and they form characteristic beads on the fibrous roots of vegetation; they persist independently of cultivation whether the soil is dry or moist. The granular structure is best developed in a virgin chernozem, being associated with a sufficient proportion of clay and humus, both being fairly completely saturated with calcium. The name " crumb " or " cloddy " is applied to the less perfectly developed structure readily changed by cultivation, and forming uneven, irregular units that crumble to powder. British soils have generally a " crumb " structure in this sense, although some old grassland soils approach the " granular " structure.

Aggregate Analysis.

(1) *The Aggregates as they Exist.*—W. Kubiena [1] has attempted to classify the smaller aggregates by observing in thin sections of the soil under a low power microscope the different ways in which the particles cluster together. Thus there may be small clusters of very fine particles between bare sand grains, or the fine particles may coat the sand grains and so cause them to stick together.

Many approximate methods have been used for determining the size of the aggregates in the soil. In general the methods are not comparable, as they do not measure the same properties: it is indeed not yet possible to decide exactly what property should be measured. Simple operations as sampling and air-drying, especially if followed by wetting, cause appreciable alteration in the structure. Keen [2] and others have estimated the numbers and sizes of aggregates existing in the field by gently sieving a spadeful of soil through a bank of sieves. If the soil is wet, however, the finer aggregates tend to stick together and do not pass the finer sieves. A. T. Tiulin [3] tried to overcome this difficulty by sieving in benzene or paraffin. Another method used by Tiulin is to sieve under water through a bank of sieves so as to determine the distribution of the structural units that are stable in water and might therefore be expected to persist in the field when it is wet. Here, too, the results are variable, since the size distribution of the crumbs is much affected by the rate of wetting.

(2) *The Units Composing the Aggregates.*—One view of soil structure is that the soil components are built up into units, which are related to their constituents somewhat as molecules are to atoms, and which persist through all the ordinary changes to which the soil is subjected. Various methods have been devised for studying these units: they differ from

[1] *Soil Res.*, 1935, 4, 380. [2] *Emp. J. Expt. Agric.*, 1933, 1, 97.
[3] *Trans. Gedroiz Inst. Fert.*, 1933, 2, 5.

the mechanical analysis of the ultimate constituents only in that the preliminary treatment is much gentler, being toned down to prevent the breaking up of the units. Demolon and Henin [1] shake the soil in an end-over-end shaker for half an hour in a dilute calcium nitrate solution before analysis, while many European drainage experts use the more drastic method of boiling the soil with water for two hours.[2]

It is not known how stable these units are. Some investigators regard them as sufficiently stable to be independent of the conditions, and dependent only on the soil properties. If this were so the results of the analyses for a particular plot should be the same whenever the sample was taken. In actual fact the results vary whatever method is used, except perhaps the " International B " method.[3] No long-continued observations have yet been published, and hence it is not possible to discuss the influence of different climatic factors.

Summary of the Properties of Calcium, Magnesium, Sodium, and Acid or Hydrogen Soils.

Calcium Soil.—This is the normal fertile soil of humid and temperate regions to which most methods of agriculture are adapted. It is neutral and stable, and its physical properties are eminently suitable to plant growth and to cultivation. It is the soil the farmer prefers. It forms on freezing or on drying a good crumb structure which is not destroyed by rain, and, in comparison with soils saturated with other bases, holds more water in the air-dry condition, and less under wet conditions. It can be cultivated over a larger range of moisture contents, is less sticky, more permeable, and therefore drains more easily. It can also accumulate neutral humus, which not only intensifies the desirable physical properties of the soil but

[1] *Soil Res.*, 1932, 3, 1.

[2] This method is known as the International Method B for mechanical analysis and is described in *Proc. 2nd Int. Cong. Soil Sci.*, Leningrad and Moscow, 1932, 1, 14.

[3] See " The Dispersion of Soils in Mechanical Analysis," *Imp. Bur. of Soil Sci. Tech. Comm.* No. 26, 1933.

also renders it more fertile by acting as a reserve of plant nutrients. It forms a favourable environment for plant roots by maintaining good air and water conditions.

Magnesium Soil.—In these the exchangeable magnesium is present in larger amounts than usual. Its effect, as shown by Joseph and Oakley,[1] is to intensify the clay properties much as sodium does. Instances have been studied by Kelley in California, by de 'Sigmond in Hungary, and others[2] (p. 301).

Sodium Soil.—Sodium clay easily hydrolyses, giving to the solution an alkaline reaction which is unfavourable for the growth of most plants. In the presence of rain water, or any other fairly pure water, it is deflocculated and consequently possesses very undesirable physical properties. It is very sticky, impervious to air, and dries into hard large lumps which break down in water to a paste. It is, therefore, very difficult to work and forms an unfavourable environment for plants. If, however, the water contains sufficient salts to keep the soil flocculated its physical properties are much improved, for it remains more permeable to water and air, and forms a better crumb structure that remains stable under this water. Provided the water is not too alkaline to be toxic to the plants, *i.e.* if the salts are only chlorides and sulphates and not carbonates, the soil forms a tolerably good environment for the growth of many plants.

Acid or Hydrogen (Aluminium) Soil.—This commonly occurs in wet regions or regions of low evaporation, and is formed by the washing out of the bases from the original soil by the percolating water.[3] The process goes on easily, for the rain water commonly contains carbon dioxide and other acids, so that a regular supply of hydrogen ions is always forthcoming to displace other cations. As already

[1] A. F. Joseph and H. B. Oakley, *J. Agric. Sci.*, 1929, **19**, 121.

[2] *E.g.* L. P. Rozov, *Pedology*, 1932, **27**, No. 3, p. 304.

[3] A. Åslander (*Nord. JordbrForsk.*, 1928, **10**, 177) gives illustrations emphasising the fact that acidity in soil is not determined by "acid rocks" or "basic rocks" but by rainfall.

pointed out, hydrogen ions, when once attached to the clay, are very firmly held. When the process of acidification has reached a certain stage easily soluble iron and aluminium compounds appear, some of which are toxic to plants; they also bring about a fixation of phosphate and so reduce the supplies available to the plant. The acid humus may act in the same way. Some of the aluminium may combine with the clay complex (p. 156).

The agricultural treatment consists in adding lime or calcium carbonate.

Effect of Artificial Fertilisers on Soils.

Artificial fertilisers are salts added by farmers to soils in order to increase the supply of nutrients to the crops. They interact with the clay and the humus in the different ways already indicated, but as the effects are of importance to the growing plant they are recapitulated here for convenience of reference.

Ammonium Sulphate.—The first reaction appears to be the ordinary base exchange, ammonium displacing some of the reactive calcium :—

$$\underset{\text{insoluble}}{(\text{Clay complex})\,Ca} + \underset{\text{soluble}}{(NH_4)_2SO_4} = \underset{\text{insoluble}}{(\text{Clay complex})\,NH_4} + \underset{\text{soluble}}{CaSO_4}$$

The calcium sulphate is readily washed out in the drainage water.

The next change is the nitrification of the ammonium with production of calcium nitrate. This then undergoes two changes :—

(1) Some is washed out of the soil and lost.

(2) Some is taken by growing plants, the process leaving some of the calcium in the soil.

Thus the final effect of sulphate of ammonia is to convert an equivalent amount of calcium into sulphate, which is lost from the soil; and a second equivalent into nitrate, part of which is lost and part regenerated.

If the whole of the calcium nitrate were lost by leaching, the net loss of $CaCO_3$ per 100 lb. of sulphate of ammonia applied would therefore be 150 lb.

If none of the calcium nitrate were lost, but all its nitrogen taken up by plants and the whole of the calcium left in the soil, the net loss would be half this, *i.e.* 75 lb.

In normal conditions the loss of calcium carbonate comes in between these two extremes: the various estimates are, per 100 of sulphate of ammonia,

Hudig	100
Hartwell and Damon [1]	110
E. M. Crowther [2]	112
Pierre [3]	120

So long as the soil contains a reserve of calcium carbonate the loss falls on this substance and not on the exchangeable calcium. At the end of 80 years, the amounts of exchangeable bases contained in the Broadbalk plots, treated every year with 200 lb. sulphate of ammonia, are given in Table 41.

TABLE 41.—EXCHANGEABLE BASES IN BROADBALK SOILS, PERCENTAGE OF DRY SOIL.[4]

No Manure.		Sulphate of Ammonia only.	Super, and Sulphates of Potash, Magnesia, and Soda.		
			Alone.	+ Sulphate of Ammonia.	+ Nitrate of Soda.
	Plot 3.	Plot 10.	Plot 5.	Plot 7.	Plot 16.
CaO	0·380	0·381	0·335	0·409	0·403
MgO	0·015	0·014	0·019	0·018	0·025
K_2O	0·020	0·014	0·051	0·053	0·045
Milligram-equivalents per 100 gm. dry soil.					
CaO	13·57	13·60	11·96	14·61	14·39
MgO	0·75	0·70	0·95	0·90	1·25
K_2O	0·42	0·30	1·08	1·12	0·95

[1] *J. Amer. Soc. Agron.*, 1927, **19**, 843.

[2] *Fifty Years of Field Experiments at Woburn*, E. J. Russell and J. A. Voelcker (1936), p. 334.

[3] *J. Amer. Soc. Agron.*, 1928, **20**, 270.

[4] H. J. Page and W. Williams, *Trans. Faraday Soc.*, 1925, **20**, 573.

In absence of calcium carbonate, however, the replaceable calcium is removed from the soil. At Woburn the effect of adding sulphate of ammonia at the rate of 200 lb. per acre for 30 years, and 100 lb. per acre for a further 20 years is shown, on the barley plots, by the following figures :—

AMOUNTS OF EXCHANGEABLE CALCIUM, EXPRESSED AS CaO, PER CENT. OF DRY SOIL.

No Manure.	Sulphate of Ammonia only.	Nitrate of Soda only.	Super, and Sulphate of Potash.		
			Alone.	+ Sulphate of Ammonia.	+ Nitrate of Soda.
0·105 *p*H 5·4	0·025 *p*H 4·5	0·144 *p*H 5·8	0·140 *p*H 6·0	0·039 *p*H 4·8	0·150 *p*H 5·8

Finally, after serious loss of exchangeable calcium, the soil becomes acid, and contains soluble iron and aluminium salts harmful to plants. The fact was established by Wheeler in Rhode Island in 1891 ; and quite independently, but a little later, the acidity was demonstrated by J. A. Voelcker at Woburn, where, the plots being permanent, the effect is continuously demonstrated.

Superphosphate of Lime.—Of all artificial manures this is used in largest quantity by farmers ; it is made by adding sulphuric acid to mineral calcium phosphate, and thus contains about half its weight of calcium sulphate ; the rest is soluble mono-calcium phosphate, phosphoric acid, and water. As soon as it reaches the soil the phosphate becomes insoluble, being absorbed, as already described on page 217. Only about 25 per cent. of it is absorbed by the crop, the rest being unavailable.

Superphosphate is sometimes, though incorrectly, regarded as an acid manure, but it has no appreciable effect on the *p*H value or exchangeable calcium of the Rothamsted or Woburn soils.[1]

[1] E. M. Crowther, *J. Agric. Sci.*, 1925, **15**, 222 ; E. M. Crowther and J. K. Basu, *ibid.*, 1931, **21**, 689.

Table 42 shows that the calcium sulphate contained in the superphosphate has not increased the availability of the potassium: it has led to no gain in weight of potassium in the crop. Briggs and Breazeale obtained a similar result on Californian soils.[1]

TABLE 42.—EFFECT OF SODIUM AND MAGNESIUM SULPHATES IN INCREASING THE SUPPLY OF POTASSIUM TO THE PLANT. LAWES AND GILBERT (1884).

	Ammonium Salts only.	Ammonium Salts + Superphosphate.	Ammonium Salts + Super. + Sulphate of Sodium.	Ammonium Salts + Super. + Sulphate of Magnesium	Ammonium Salts + Super. + Sulphate of Potassium.	Ammonium Salts + Super. + Sulphates of Sodium, Magnesium, and Potassium.
1852-1861.	Plot 10.	Plot 11.	Plot 12.	Plot 14.	Plot 13.	Plot 7.
K_2O in ash of straw, per cent. . .	18·8	14·8	20·1	22·0	24·1	23·7
K_2O in ash of grain, per cent. . .	33·9	31·7	32·8	32·6	32·9	32·9
Weight of K_2O in ten whole crops, lb.[3] . . .	300	309	454	498	532	560
1862-1871.						
K_2O in ash of straw, per cent. . .	14·5	14·1	17·2	18·5	25·0	24·6
K_2O in ash of grain, per cent. . .	34·1	32·1	33·3	33·1	33·5	33·4
Weight of K_2O in ten whole crops, lb.[3] . . .	240	260	378	391	552	530
Total amount of K_2O taken by crop during the twenty years, lb. . .	540	569	832	889	1084	1090

Potassium Sulphate.—This increases the amount of replaceable potassium, apparently at the cost of the calcium and magnesium. Some other action takes place, for a further quantity is retained by the soil in an insoluble but not exchangeable form. Truog has put forward the ingenious hypothesis that it is converted into muscovite.[2]

[1] *J. Agric. Res.*, 1917, **8**, 21.

[2] N. J. Volk, *Amer. J. Sci.*, 1933, **26**, 114.

[3] About one quarter is in the grain and the rest in the straw.

Both at Rothamsted and at Woburn sulphate of potash is without effect on the reaction of the surface soil, though it increases the acidity of the sub-soils on the acid plots,[1] possibly through the washing down by rain of the acid liberated by cationic exchange. The effect on the exchangeable bases is shown in Page and Williams' analyses of the Broadbalk soil: the results in milligram-equivalents per 100 grm. of dry soil are given in Table 43.

TABLE 43.—EXCHANGEABLE BASES IN BROADBALK SOIL.[2]

Milligram Equivalents per 100 *grm. Dry Soil.*

	Unmanured.	Sulphate of Ammonia and Super.	Sulphate of Ammonia, Super. and Sulphate of Potash.	Sulphate of Ammonia, Super. and Sulphate of Soda.
CaO	13·57	15·32	14·89	16·29
MgO	0·75	0·70	0·50	0·70
K_2O	0·42	0·32	0·89	0·32

Sodium Sulphate.—On the Broadbalk wheat field, sulphate of soda acts rather differently from sulphate of potash. It causes no diminution in the amount of replaceable calcium or potassium, but on the contrary an increase in the calcium. Apparently, therefore, the sodium has not replaced calcium or potassium, yet something has certainly happened, for more potassium is taken up by the crop. The Broadbalk wheat receiving sulphate of soda, but no sulphate of potash, contains more potassium than wheat on the adjoining plot receiving no sulphate of soda (Table 42).

Magnesium sulphate has the same effect. From Table 42 it appears that in the twenty-year period, 1852 to 1871, the sodium sulphate had enabled the plant to take up an additional 263 lb. of K_2O, whilst the magnesium sulphate has furnished it with an extra 320 lb. over and above what the crop on Plot 11

[1] E. M. Crowther, *J. Agric. Sci.*, 1925, **15**, 222; E. M. Crowther and J. K. Basu, *ibid.*, 1931, **21**, 689.

[2] *Trans. Faraday Soc.*, 1925, **20**, 573.

obtained. Calcium sulphate, on the other hand, has had no effect.

Sodium Nitrate.—The action of this substance was studied by A. D. Hall [1] owing to its technical importance. When added regularly in quantities of 5 to 10 cwt. per acre (not unusual for market garden crops or early potatoes), nitrate of soda is liable to spoil the texture of certain soils. The field evidence, however, is conflicting. A solution of nitrate of soda continually percolated through the light sandy soil at Woburn converted it into a mass like concrete. But the permanent wheat and barley plots in spite of fifty successive annual dressings of nitrate of soda (2¼ cwt. per acre) show no particular evidence of bad tilth, except occasionally in wet winters. Nitrate of soda conserves the reactive or exchangeable calcium and so reduces the net loss of calcium carbonate, and to this extent prevents the soil from becoming acid (p. 232).

SUMMARY.

Change in Soil Reaction produced by Long-continued Use of Manures.

Acidity Increased.	Little Effect.	Acidity Reduced.
Sulphate of ammonia.	Superphosphate.	Nitrate of soda.
Protein (blood, hoof meal, etc.).	Potassium salts.	Basic slag.
Leguminous green [2] manure crops.	Farmyard manure.	Calcium cyanamide.
	Non-leguminous green [2] manure crops.	

Calcium Oxide and Calcium Carbonate.—The effect of these substances in neutralising soil acidity and saturating the clay and humus complexes with calcium has already been discussed (p. 214). Both oxide and carbonate have in general the same action in the soil except that the oxide used in large quantities has a partial sterilising effect (p. 476) and decomposes

[1] *Trans. Chem. Soc.*, 1904, **85**, 964-971.

[2] P. S. Burgess, *R.I. Agric. Expt. Sta. Bull.* No. 189, 1922. The difference is attributed to the greater production of nitrate, and therefore greater draft on the bases, by leguminous green crops.

some of the humus. It does not long persist in the soil as such, however: some of it reacts at once with the soil acids and appears as exchangeable calcium, while the rest is slowly but quantitatively converted into carbonate: some of this goes into solution as bicarbonate. The fate of the added lime is shown in Hissink's analyses (Table 44).

TABLE 44.—FATE OF LIME ADDED TO SOILS OF VARIOUS REACTIONS. HISSINK.

	Soil not Neutralised.				Soil Neutralised.		
	Soil No.				Soil No.		
	VII.	IV.	V.	VI.	III.	I.	II.
*p*H of soil: unlimed	4·6	4·8	5·2	6·1	6·3	7·6	8·0
limed .	5·5	6·8	5·9	6·6	7·2	7·8	8·0
Per cent. of added CaO retained as exchangeable CaO .	88	100	95	50	28	12	2
Left as $CaCO_3$.	12	Nil.	5	50	72	88	98

Several other effects are produced. The calcium flocculates the clay, bringing it into a better physical texture. It protects both potassium and magnesium against loss by leaching, as shown in the extensive lysimeter experiments at Knoxville, Tennessee.[1] It does not, however, as the older agricultural chemists supposed, liberate potassium in the soil from its insoluble compounds.[2] It stimulates bacterial action in the soil and so facilitates the decomposition of the organic matter, but the increased plant growth resulting from its use may more than compensate for this by adding extra plant residues to the soil. The soil of the limed halves of the Park Grass plots is richer, on the average, in both carbon and nitrogen

[1] W. H. MacIntyre, W. M. Shaw, and J. B. Young, *Soil Sci.*, 1923, **16**, 217; confirmed also by J. Hendrick, *Trans. Highl. Agric. Soc. Scot.*, 1930, **42**, 1, and O. C. Magistad, *Soil Sci.*, 1930, **30**, 243, who shows that calcareous soils have a lower rate of leaching of potash than have non-calcareous soils.

[2] For the literature see O. H. Sears, *Soil Sci.*, 1930, **30**, 325.

than that of the unlimed. There seems little difference in effect between the oxide and carbonate so long as they are used only in moderate dressings: examination of the long-continued Pennsylvania plots [1] showed no significant difference in organic matter content whether oxide or carbonate had been applied. The effect on the solubility of the phosphate varies: in some instances, usually on acid soils (pp. 220, 241), an increase is recorded, in others not. Heavy dressings of lime have sometimes caused chlorosis or other diseases related to deficiencies of the "minor" elements, including iron, manganese, and boron (p. 101).

These various calcium reactions have a great effect on vegetation, and lime and limestone are among the oldest of manures.[2]

The Plant Nutrients in the Soil.

The Nitrogen Compounds.

The nitrogen compounds in the soil are derived mainly from protein which, in turn, comes from residues of plants or soil organisms. They fall into two groups: inorganic, chiefly ammonia and nitrate, which, however, represent only a small fraction of the nitrogen: and organic, complex insoluble compounds of unknown but probably protein-like constitution. The organic compounds are again divided into:—

(1) Material dating back to the time when the soil was first deposited, which although originally protein, has undergone considerable change, becoming highly resistant to chemical or biological action.

(2) Protein-like compounds of recent origin, occurring in the form of a very stable complex combination with humus.

(3) Protein of plant cells and micro-organisms which is readily decomposable by micro-organisms but has not yet been decomposed.

[1] J. W. White and F. J. Holben, *Soil Sci.*, 1924, **18**, 201.

[2] Pliny described with evident approbation the method in which the Belgæ used the chalk—and his description holds almost exactly for the traditional method followed till recently in the Home Counties (C. Plinii Secundi, *Naturalis Historiæ*, Lib. 17, Cap. 4). See also E. J. Russell, *J. Bd. Agric.*, 1916, **23**, 625.

The total nitrogen in English arable soils is usually about 0·15 per cent.; in pasture soils about 0·3 per cent.; higher

TABLE 45.—TOTAL AND SOLUBLE NITROGEN IN DIFFERENT SOILS.

	Old Arable Land,[1] Rothamsted.			Old Grass Land,[2] Rothamsted.		Prairie Soil, Manitoba.
	No Manure since 1839.	Artificial Manure since 1843.	Farmyard Manure since 1843.	No Manure since 1856.	Artificial Manure since 1856.	No Manure.
Total N, per cent. .	·0966	·115	·217	·260	·230	·618
Soluble N, per cent. .	·050	·062	·114	·173	·149	·230
Ratio soluble to total when total = 100 .	51·8	53·8	52·5	66·3	65·0	37·2

amounts are present in chalk soils and still higher in fen, moorland, and black prairie soils. About half of the nitrogen in arable soil is contained in compounds soluble in alkalis, and a small proportion in unstable compounds readily breaking down to ammonia. About 0·0002 per cent. (*i.e.* 2 parts per 1,000,000) is present as free or combined ammonia in arable soils not rich in organic matter, sometimes more, however,[3] and up to five times this quantity in grassland or heavily dunged arable soils; much larger quantities occasionally occur as in heated soil, but abnormal growth effects are then produced.[4] The amount of nitrogen present as nitrate varies considerably; rich garden soils may contain 60 or more parts per 1,000,000 (·006 per cent.), arable soils 2 to 20 parts (·0002 to ·002 per cent.), pasture soils rather less and wood-

[1] This was old arable land in 1621.

[2] Grass for very many years.

[3] G. André (*C.R.*, 1903, **136**, 820) obtained higher results in early spring which he attributed to the cessation of nitrification, but not of ammonification, during winter.

[4] See E. J. Russell and F. R. Petherbridge, *J. Agric. Sci.*, 1913, **5**, 248.

land soils still less.[1] The fluctuations are considerable; plants and rain rapidly remove nitrates, and bacterial action rapidly forms them. The producing agencies are active in

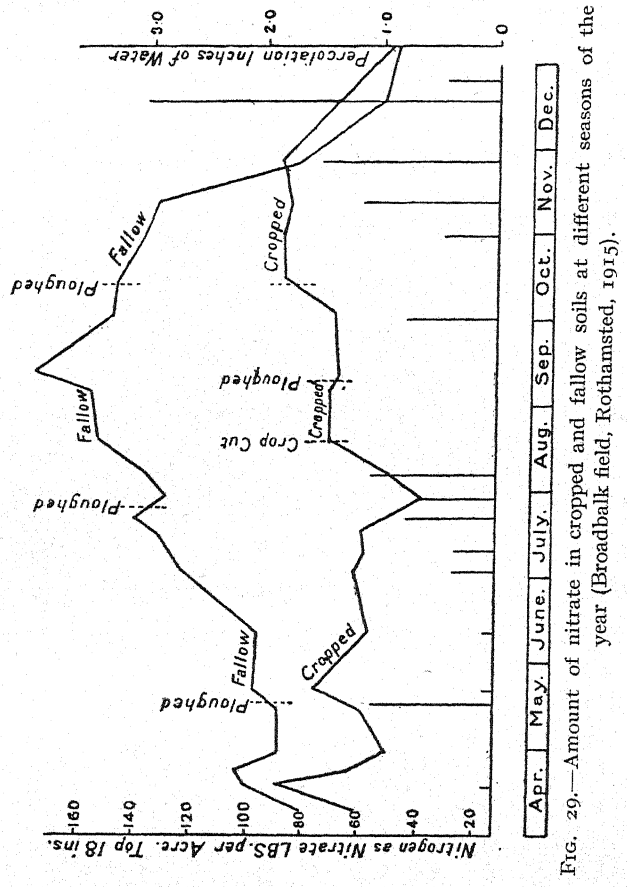


FIG. 29.—Amount of nitrate in cropped and fallow soils at different seasons of the year (Broadbalk field, Rothamsted, 1915).

spring, and work throughout summer and autumn, while the removal agencies are active in summer and winter. Thus the amount of nitrate actually present in the soil of arable land

[1] It is sometimes stated that woodland soils do not contain nitrates and are unsuited for nitrification, but Fr. Weis (*Zbl. Bakt.*, Abt. II, 1910, **28**, 434) showed this to be incorrect.

carrying a crop is usually highest in spring, falls in summer, often rises somewhat in autumn, and falls again in winter, as shown in Fig. 21 (see also p. 474).[1] On fallow land the accumulation is continuous, but it may be less rapid in summer than in spring. In grassland soils, where a series of dynamic equilibria exists between successive stages of the nitrogen cycle, the levels both of ammonia and nitrate are more constant.[2]

In South Africa [3] and in Australia [4] the fluctuations in arable soil are of similar character, but, as one might expect, the marked rise is from October to December. Prescott shows that the level of accumulation during the spring and summer is about 20 parts of nitrate nitrogen per million of soil, very similar to English values. The chief factor determining the rate of accumulation is the supply of soil moisture.

In normal conditions the nitrate and ammonia together rarely account for more than 1 per cent. of the nitrogen in the soil.

The Phosphorus Compounds of the Soil.

In neutral or nearly neutral conditions much of the inorganic phosphorus is combined with calcium, and Bassett [5] has shown that in neutral conditions it most probably occurs as hydroxyapatite—

$$(Ca_3P_2O_8)_3Ca(OH)_2,$$

this being the solid phase stable over a range extending from faintly acid to alkaline conditions: any phosphate such as superphosphate or basic slag added to the soil as fertiliser would tend to be converted into this substance (p 232).

[1] For American data see R. Stewart and J. E. Greaves, *Zbl. Bakt.*, Abt. II, 1912, **34**, 115.

[2] H. L. Richardson, *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 219.

[3] T. D. Hall, *Soil Sci.*, 1921, **12**, 301.

[4] J. A. Prescott and G. R. Piper, *J. Agric. Sci.*, 1930, **20**, 517.

[5] *Trans. Chem. Soc.*, 1917, **111**, 620.

The iron and aluminium compounds formed in acid conditions have not been much investigated. The interesting mineral vivianite, an iron phosphate which is white when freshly found but rapidly becomes blue on exposure to the air, can occasionally be picked out of a wet layer of peat soil. Addition of lime to acid soils increases the solubility of the phosphate. It is commonly assumed that the lime decomposes both iron and aluminium phosphates, converting them into calcium phosphate, but Askinazy and Yarusov [1] were unable to find evidence of this.

Part of the phosphorus in the soil, however, is in organic combination, having been assimilated by plants and micro-organisms, and built up into their substance. Schollenberger [2] found about one-third of the phosphorus in this form in the soils he studied. Little is known about these organic combinations in the soil, but there is evidence that some at any rate readily break down to yield inorganic phosphates.

Some of the phosphorus is very insoluble. Marshall supposes that it can replace silicon in the clay lattice to form a stable compound.[3]

Calcium Compounds in the Soil.

The calcium compounds in the soil fall into five groups :—

(1) *Calcium Carbonate.*—Perhaps the most important single substance in the soil, the functions of which are discussed on pages 214 *et seq.*

(2) *Simple Salts.*—

(*a*) Calcium nitrate, usually present only to a very small extent (in British soils the quantity is of the order of 0·001 per cent.), but highly important as the chief source of nitrogen for vegetation.

(*b*) Calcium phosphate (p. 240).

(*c*) Calcium sulphate.

[1] *Trans. Sci. Inst. Fert.*, Moscow, No. 57, 1928.
[2] *Soil Sci.*, 1918, **6**, 365, and 1920, **10**, 127.
[3] *Ztschr. Kryst.*, 1935, **91**, 433.

In humid climates the amounts of (*b*) and (*c*) are small, and in analysis are usually included under (3) and (4); in arid conditions, however, considerable quantities of calcium sulphate may be present.

(3) The "exchangeable" calcium.

(4) "Acid soluble" but non-exchangeable calcium, in combination with silicates which are easily decomposed by boiling HCl (p. 165).

(5) Stable insoluble calcium silicates usually ignored in soil investigations.

Magnesium Compounds.

Magnesium compounds generally come second in amount to calcium; they are found in each of three groups: "exchangeable," "acid soluble," and "stable insoluble"; in some soils the carbonate is present in notable quantities, and occasionally, as in the Wealden clays, there is a fair amount of the sulphate.

Potassium Compounds.

The chief potassium compounds in the soil are silicates, but their effect on plant growth is much greater when they occur in the finer, than in the coarser, portions of the soil. Dumont [1] instances two soils of nearly equal potassium content, one from La Creuse responding to potassic fertilisers, while the other from Grignon does not: in the former the

TABLE 46.—DISTRIBUTION OF POTASSIUM AMONG SOIL PARTICLES. DUMONT.

	Per Cent. of K_2O in Soil.	Response to Potassic Fertilisers.	Per Cent. of "Argile."	Per Cent. K_2O in "Argile."	Percentage Distribution of Potash in Soil.		
					"Sable Grossier."	"Sable Fin."	"Argile."
Grignon .	0·85	Nil	16·8	0·94	16·6	65·8	17·7
La Creuse .	0·89	Good	4·5	0·51	70·9	26·4	2·7

[1] *C.R.*, 1904, **138**, 215.

potassium is present mainly in the coarser material, in the latter mainly in the finer (Table 46).

In arid conditions the sulphates, chlorides, and carbonates of sodium, potassium, and magnesium may occur in sufficient amount to injure vegetation. The soils are then described as saline soils (p. 295). In humid conditions these salts are washed out by the rain water ; no clear case is known in Britain where they accumulate apart from flooding with sea water (p. 334).

Soluble Iron, Aluminium, and Manganese Compounds in the Soil.

The amounts of iron, manganese, and aluminium present in soluble form in the soil depend on the reaction. In slightly alkaline conditions their solubility may be so low that the quantities of iron and manganese available to the plant may be insufficient and the deficiency troubles already mentioned (p. 101) may set in. In slightly acid conditions the solubility is greater and the supplies are adequate for plant growth. As the acidity increases the amounts coming into solution may be so large as to injure plants.[1]

The range over which compounds remain insoluble appears to be—[2]

For aluminium about *p*H 4 to 10 : minimum solubility
For iron ,, *p*H 3 to 9. about *p*H 6.
For manganese ,, *p*H 7 to 9.

As an illustration, Magistad [3] found the following amounts of aluminium in the soil solutions of natural soils :—

*p*H .	4·87	5·14	5·30	5·50	6·90	9·01
Al_2O_3 .	1·2	2·0	0·7	0·3	0·7	31·0

(parts per million of solution)

[1] H. G. M. Jacobson and T. R. Swanback, *J. Amer. Soc. Agron.*, 1932, **24**, 237 ; F. Steenbjerg, *Tidsskr. Planteavl*, 1935, **40**, 797 ; *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 198.

[2] H. T. S. Britton, *Hydrogen Ions* (1929), London.

[3] *Soil Sci.*, 1925, **20**, 181 ; see also R. H. Carr and P. H. Brewer, *Ind. Eng. Chem.*, 1923, **15**, 634.

Ferric oxide may be found in soils of any region, and it may occur either in the red or the yellow states. The yellow form, limonite, is common in cold wet regions where it is the most easily soluble of all the iron minerals. The red form is common in humid tropical and sub-tropical conditions, indeed it has been regarded as essentially the product of these conditions, but this is not entirely correct: red soils occur in cold moist northern climates also, and yellow ones occur in warm conditions. Vilensky [1] supposed the yellow to be an earlier stage of weathering, which passes later into the red. The parent rock, however, has considerable influence: the yellow form is more common in soils from sedimentary rocks, and the red in soils from crystalline rocks, especially granites.

Aluminium hydroxide is not easily distinguishable from the easily decomposable silicate though various methods [2] are in use for this purpose. Apparently it does not occur to any marked extent in cool or temperate conditions: Marbut found it only in the warmer regions of the United States, *e.g.* South Carolina.

Even in tropical soils Hardy found only small amounts, usually less than 5 per cent.; only in the bauxitic clays was more than 12 per cent. present. The clay fractions contained less than the rest of the soil, suggesting that the alumina tends to segregate into concretions of the size of silt or larger particles.

Only a small part of the iron was in the form of free oxides, but this, unlike the alumina, tended to concentrate in the clay.

Manganese is probably present in the soil as the dioxide or the hydrated oxide $Mn_2O_3 . H_2O$; and it probably accounts for some of the catalytic changes produced in soil, such as the rapid decomposition of hydrogen peroxide [3] and the decomposition of phenol.[4] It interferes with the quinhydrone electrode for determining *p*H values (p. 213).

[1] *Soil Res.*, 1928, **1**, 108.

[2] Among others, those of Tamm (ammonium oxalate), *Medd. Skogsförsöksanst.*, 1922, **19**, 387; Mattson (hot saturated aluminium chloride), *Proc. 1st Int. Cong. Soil Sci.*, Washington, 1927, **2**, 199; F. Hardy (alizarin), *J. Agric. Sci.*, 1931, **21**, 150.

[3] W. O. Robinson, *Soil Sci.*, 1929, **27**, 335.

[4] N. N. Sen Gupta, *J. Agric. Sci.*, 1921, **11**, 136; 1925, **15**, 497.

CHAPTER IV.

THE SOIL IN NATURE: I. CHANGES IN ITS MINERAL COMPOSITION.

A CONTINUOUS series of changes goes on in the soil. Some are so slow that they are completed only in geological periods of time, while others, in which the growing plant is involved, are more rapid but they are cyclic or reversible and more or less balance each other, the final equilibrium changing only very slowly so long as the surrounding conditions remain in general unaltered. The result is that a natural soil suffers but little net change from year to year, in spite of the numerous reactions taking place in it. Where, however, it is brought into cultivation the various equilibria are disturbed and rapid net changes occur until the new equilibria are reached, after which net change again becomes slow. If the arable land is converted into grassland another set of levels is reached but again the net annual changes are small so long as the land remains permanently in grass. The reactions in the soil have therefore to be studied in relation to the existing equilibria and not merely as isolated phenomena.

The mineral constituents of the soil undergo four general kinds of change :—

(1) Disintegration, which breaks them down into small particles, and so leads to a certain amount of mechanical separation.

(2) Decomposition brought about by three sets of agents :—

(*a*) water and carbon dioxide, which, acting as carbonic acid, very slowly decompose the complex silicates forming clay minerals, silica, oxides of iron, aluminium,

manganese, etc., and carbonates of calcium, magnesium, potassium, sodium. Oxidation of the sulphur leads also to the formation of sulphates of the four last-named elements; other salts, chlorides, phosphates, etc., are also formed. This action goes on at all depths to which carbon dioxide can gain access.

(*b*) organic acids, which not only effect certain decompositions but assist in dissolving or dispersing the hydroxides of iron and aluminium and silicon, so that these become mobile in the soil. This action, however, goes on near the surface only: it rarely occurs at greater depths than 2 feet.

(*c*) alkalis released from the rock during weathering, which intensify the dissolution of the silica, leaving a residue very rich in iron and aluminium oxides. This action, like that of carbonic acid, may occur at considerable depths in the soil, and does not suffer from the restriction shown by (*b*).

(3) Recombination of some of these substances into new mineral substances.

(4) Redistribution of these various products as the result of the movement of water through the soil, the effect of the growing plant, of animals, especially earthworms, of the soil micro-organisms, and especially of the organic substances formed when the plant dies and its residues mingle with the soil.

Decomposition Effected by Carbonic Acid: Weathering.

This process is so slow that its study properly belongs to geology and mineralogy rather than soil science. It is characterised by the fact that it is not confined to the upper layer of the soil but can take place at any depth to which water and carbonic acid can penetrate.

Removal of the Products of Decomposition.

Effects of Leaching.—Rain water soaking through the soil dissolves some of the products of decomposition and washes them away. The most mobile constituents are the chloride, sulphate, potassium, and sodium ions; calcium comes next, then silica liberated from the complex silicates; all these appear in the drainage water and are carried down to the rivers and finally to the sea. The least mobile are the oxides of iron and aluminium, the quartz and possibly the kaolin. Polynov gives the following relative orders of leaching out :—

$$SiO_2 > Al_2O_3 > Fe_2O_3\,; \quad Ca > Mg\,; \quad Na > K.$$

In consequence of the difference in solubility of silica and the sesquioxides the ratio SiO_2/R_2O_3 in the residual material falls during the leaching process; in the original rock it may be about 6; in many soils it is about 4, and in extreme cases it falls to 2 or less.[1]

Four general stages are distinguished by Polynov [2] in the removal of the products of decomposition :—

(1) Mechanical disintegration.

(2) Loss of the most mobile ions : —Cl and $—SO_4$, leaving, however, much basic material (calcium and magnesium) and silicates. This is the saturated siallitic stage.

(3) Loss of calcium and other basic material, leaving acid material : this is the acid siallitic stage.

(4) The loss of silica which leads to the accumulation of iron and aluminium hydroxides; the lateritic or allitic stage.

All four stages are represented in various groups of soils.

The first stage is represented in very dry climates by the desert soils and in humid climates by very recent soils. The

[1] For an interesting discussion of the process, showing the resting stages that might be expected to occur in the various soil groups discussed in this chapter, see H. G. Byers, *Trans. 3rd Int. Cong. Soil Sci.*, 1935, 1, 76; also H. G. Byers, L. T. Alexander, and R. S. Holmes, *U.S.D.A. Tech. Bull.* No. 484, 1935. Good work on this subject is done in Finland : see Antti Salminen, *Agrogeologisia Julkaisuja*, Helsinki, No. 40, 1935.

[2] B. B. Polynov in *Studies in the Genesis and Geography of Soils* (1935), p. 19.

second stage is represented in soils of moderately dry continental areas. The soils are characterised by the presence of (*a*) calcium carbonate, usually in fair quantity except where the parent material is an acid igneous rock: (*b*) saturated silicates; (*c*) alumino- and ferro-silicates; (*d*) hydrous ferric hydroxide formed from iron minerals.

The third stage is less easily characterised because recombination always occurs, forming some clay minerals, secondary micas, etc.

In the fourth stage quartz and the sesquioxides are the chief end products, and these give rise to the lateritic soils and the laterites.

It was formerly widely supposed that these groups represented independent forms of weathering, each determined by a particular set of climatic conditions. On the more modern view climate does not alter the direction of the weathering process, but only the rate at which the various stages are passed through.

Losses Caused by Leaching in Temperate Climates.

Under the influence of rain in cool climates of low evaporation the soluble sodium is almost completely washed out from the soil, as is also the exchangeable sodium in the clay and the humus. The removal is complete: the sodium finally appears in the sea water where it is the dominant cation. Calcium is also removed, but more slowly and much less completely: calcium sulphate most easily and calcium carbonate after conversion into the bicarbonate. The anions easily removed are $—NO_3$, $—SO_4$, —Cl, and $—HCO_3$, and these four, together with Na and Ca, are the chief constituents of drainage water in this country. Table 47 gives the data for Rothamsted, and Table 48 for Aberdeen.

It will be observed that the total concentration of the Rothamsted drainage water varies from ·02 to ·05 per cent. The high amount of sodium in the Aberdeen drainage water

TABLE 47.—COMPOSITION OF DRAINAGE WATER: ANALYSES OF DRAINAGE WATERS FROM CULTIVATED FIELDS: PARTS PER MILLION OF SOLUTION.

	Rothamsted: Broadbalk Field.[1]			Field at Gottingen.[2]	
	No Manure.	Dung.	Complete Artificials.	Highest Result.	Lowest Result.
	Plots 3 and 4.	Plot 2.	Plot 6.		
CaO	98·1	147·4	143·9	184	157
MgO	5·1	4·9	7·9	46·4	31·3
K_2O	1·7	5·4	4·4	3·7	1·7
Na_2O	6·0	13·7	10·7	—	—
Fe_2O_3	5·7	2·6	2·7	—	—
Cl	10·7	20·7	20·7	—	—
SO_3	24·7	106·1	73·3	59·2	43·5
P_2O_5	·6	—	1·54	—	—
SiO_2	10·9	35·7	24·7	—	—
N as NH_3	·14	·20	·24	—	—
N as Nitrate	15·0	62·0	32·9	8·2	1·0
Organic matter, CO_2, etc.	67·7	77·3	84·6	—	—
Total solids	246·4	476·0	407·6	—	—

TABLE 48.—COMPOSITION OF DRAINAGE WATER FROM CROPPED LYSIMETERS, ABERDEEN.[3]

	Parts per Million in Drainage Water.			Lb. per Acre per Annum.		
	No Manure.	Complete Manure.		No Manure.	Complete Manure.	
		No Lime.	Lime.		No Lime.	Lime.
CaO	19·3	21·0	29·9	76·1	83·0	111·5
MgO	7·8	7·9	9·4	30·7	31·9	35·3
K_2O	3·2	2·9	3·6	12·8	12·3	11·5
Na_2O	16·5	17·0	22·2	66·7	70·3	70·5
Cl	13·7	14·9	15·3	59·5	65·9	66·2
SO_3	17·0	24·4	28·9	67·1	98·9	113·1
SiO_2	26·0	23·5	21·9	106·8	103·1	94·0
N	3·7	3·6	4·5	12·4	12·2	14·1

[1] A. Voelcker's (1871) analyses of five samples collected between 1866 and 1869.

[2] Von Seelhorst and Wilms' (*J. f. Landw.* 1901, **49**, 251) analyses of samples collected weekly or fortnightly, from a field between August, 1899, and August, 1900. For French data see Th. Schloesing (1866 *et seq.*).

[3] J. Hendrick and H. D. Welsh, *Proc. 1st Int. Cong. Soil Sci.*, 1928, **2**, 358. These figures are the averages for the eight years 1919-1926, during the first two of which no manure was added.

is interesting in view of the fact that the amounts of exchangeable bases in the soil are—

	Per Cent. of Total Exchangeable Bases.
CaO	85
Na_2O	4·7

Table 49 gives the loss of lime and soda from four different soils.

TABLE 49.—LOSS IN LB. PER ACRE PER ANNUM AS ESTIMATED FROM DRAINAGE WATER FROM UNMANURED SOILS.

	CaO.	Na_2O.
Rothamsted [1]	300	15
Aberdeen	76	66
Ithaca (New York State) [2]	173	78 cropped
	367	103 bare
Florida [3]	140	600

Influence of Rainfall and Temperature on the Leaching Process.

The amount of water percolating through the soils depends partly on the rainfall and partly on the temperature. At Rothamsted approximately 50 per cent. of the rain falling on uncropped land soaks through on the average. In warmer conditions, however, the percolation is less: an increase of 1° C. in the annual temperature at Rothamsted lowers it as much as a reduction of 3·5 cm. in the mean annual rainfall. Approximately the same values seem to hold for the United States (see below). These opposite effects of rainfall and temperature have been studied in detail by E. M. Crowther.[4] Using some data of Robinson and Holmes [5] on the composition

[1] Uncropped land. Percolation about 15 inches. From land covered with vegetation the losses are very much less.

[2] T. L. Lyon and J. A. Bizzell, *Cornell Agric. Expt. Sta. Mem.* 12, 1918.

[3] S. E. Collison and S. S. Walker, *Univ. Florida Agric. Expt. Sta. Bull.* No. 132, 1916.

[4] *Proc. Roy. Soc.*, 1930, B, **107**, 1.

[5] *U.S.D.A. Bull.* No. 1311, 1924.

of the clay fraction of certain widely distributed samples of American soils, he found that the molecular ratio of silica to alumina (SiO_2/Al_2O_3) in the clay fraction increased with increasing temperature and decreased with increasing rainfall, remaining constant (after allowing for the different geological origins of the parent materials) when an increase of 1° C. in the mean annual temperature is accompanied by an increase of 4 cm. in mean annual rainfall. The calcium content of these clays varies similarly with climatic conditions, an increase of 1° C. in the mean annual temperature raising it by the same amount as an increase of 3·6 cm. in rainfall would lower it.[1] When therefore rainfall and temperature increase together (as often in the States) the ratios of $\frac{SiO_2}{Al_2O_3}$ in clay from similar parent materials change but little with climatic conditions; but where, as in Russia, the rainfall tends to decrease as the temperature rises the variation in clay composition becomes much larger.

This effect of rainfall in masking temperature may explain the interesting observations of J. van Baren [2] that the weathering of limestone follows very similar lines in tropical India and in temperate Holland.

Two other effects of temperature are important: both can be related to its influence on leaching. H. Jenny [3] has shown that the clay content of soils of similar parent material increases regularly in belts from North to South in the United States; increasing temperature being apparently the dominating factor. Also when the mean annual temperature exceeds a certain limit [4] the ratio of SiO_2/R_2O_3 increases in going down the profile, while below this limit for soils other than podzols it remains fairly constant.

[1] In British units the figures are 0·75 inch reduction in percolation for a rise of 1° F., and approximately the same figures, 0·80 and 0·88 inch, as the amount of rain counteracted by 1° F. in the United States.

[2] J. van Baren, A. Te Wechel, L. Möser, C. van Aggelen, *Mitt. Geol. Inst. Wageningen*, 1930, No. 16.

[3] *Soil Sci.*, 1935, **40**, 111.

[4] 61° F. in Baver and Scarseth's experiments (*Soil Res.*, 1931, **2**, 288).

Factors Modifying the Leaching Process.

The simple sequence in the leaching processes outlined above is subject to interference from several causes.

(*a*) When the acid stage is reached owing to removal of calcium and other bases the clay nucleus becomes unstable and easily yields iron and aluminium oxides and silica which the organic acids readily convert into sols, so making them more mobile than the quartz. They are, however, readily precipitated from their suspensions, so that while being easily removed from the surface soil they are also easily deposited lower down in the soil: their mobility does not last long enough to carry them far away. Further complication arises in that iron can travel either as a ferric or a ferrous ion, as a complex compound with organic acids, as humus-iron-sol, or silica-iron-sol: so that while it usually does not penetrate as far as the alumina it sometimes goes further.

(*b*) If the drainage water cannot get away it accumulates as ground water and so the leaching process stops and none of the products are removed. The supply of oxygen being cut off, various reductions take place and a number of secondary changes occur.

(*c*) The surface of the soil being almost always undulating the movement of the drainage water, instead of being entirely vertical, is frequently somewhat lateral, so that material may be carried in from adjacent soil.

The Reversing Effects of Vegetation and of Animals Living in the Soil.

Vegetation.—By means of their roots plants assimilate from the lower levels of the soil a good deal of material that has washed down from above: it is brought up into their leaves and when these are shed the material is returned to the surface, there to suffer once more the process of leaching. Thus the process that would otherwise be a pure loss is converted into a cycle which may continue almost indefinitely to keep the substances involved near the surface. The extent

to which it occurs depends on the conditions, but where these are favourable for growth and assimilation, as in many parts of England, it becomes very marked ; indeed this might be described as one of the characteristic features of English soils. Striking examples can also be found elsewhere : Polynov [1] found that the leaves of beech and hornbeam—and other trees also—contain much more alumina in the Black Sea region than in the North, and in consequence alter the type of soil formation taking place.

APPROXIMATE PERCENTAGES OF Al_2O_3 AND SiO_2 IN THE LEAVES.[2]

	Western Europe.		Black Sea.	
	Al_2O_3.	SiO_2.	Al_2O_3.	SiO_2.
Beech . .	1½–2 per cent.	5–6 per cent.	8 per cent.	8 per cent.
Hornbeam .	½–1 ,, ,,	—	10 ,, ,,	3 ,, ,,

Another effect of the growing plant is largely to determine through its root system the distribution of the organic matter in the soil layers. The amount of organic matter is high near the surface where the roots are numerous and extensive, and where also dead leaves and stems constitute continuous supplies; it becomes much less at lower depths, where roots are few and not widely distributed.

Animals Living in the Soil.—Of these earthworms are by far the most important in temperate climates. They have been studied in detail as a result of the classical investigation by Darwin described in *Earthworms and Vegetable Mould*, one of the most interesting books on soil ever written. Earthworms produce two important effects in the soil, aerating it and mixing its constituents ; they pass large quantities of material through their bodies and eject it on the surface as

[1] *Trans. 3rd Int. Cong. Soil Sci.*, 1935, **3**, 158.
[2] B. B. Polynov, *ibid.*

"worm casts," which Darwin estimated would form a layer 0·2 inch thick in the course of a year. They are thus perpetually turning the soil over to the depth to which they operate, mingling the various soil constituents, dragging in leaves and other plant residues from the surface, and thus facilitating decomposition by the micro-organisms. The results are very striking, and are well seen in comparing soils well stocked with earthworms with those containing only small numbers. Where earthworms are active in the soil, organic matter is distributed throughout the layer in which they operate. But where in cool conditions or acid soils earthworms are few or absent, there is much less mixing; the dead vegetable matter accumulates on the surface, becoming a partly decomposed, acid, peaty mass, in which the normal soil decompositions are not completed. The surface vegetation becomes profoundly modified, only few plants being able to force their way through the mass of dead material; as they die their remains also lie on the surface, and may, if the rate of decomposition be sufficiently slow, accumulate to form a bed of peat.

The second great effect of earthworms is to facilitate aeration and drainage. They honeycomb the soil with their burrows, leaving channels along which air and water easily pass, thus saving the bulk of the soil from a good deal of the seepage to which it would otherwise be liable.

Ants.—In tropical conditions ants, termites and other insects play an important part in devouring the dead vegetation that would otherwise give rise to humus. In consequence of this and of the high activity of soil micro-organisms the supply of humic acid is usually too small to allow podzolisation to take place.

Recombinations among the Products.—The decomposition products can recombine among themselves to form new silicates or colloidal complexes which, however, differ considerably from the original rock materials and which give to the clay fraction most of its special properties. Kaolin

appears to be formed in absence of much basic material, and montmorillonite when sufficient is present.[1] Polynov found a magnesium alumino-silicate, paligorskite, in the illuvial horizons of some Russian relict soils, which appears to have been formed by the interaction of magnesium carbonate with colloidal alumina and silica.[2] Mattson[3] has set up the hypothesis that the recombination of silica with iron and aluminium hydroxides always proceeds in such a way that the products are isoelectric with the soil solution. Any change in the electrical properties of the soil solution leads to a change in the colloidal complex: if the solution becomes more acid the complex will lose sesquioxides or *vice versa*, but in all cases the equilibrium is attained only when the product and the solution are isoelectric.

Soil Classification[4]: the Soil Profiles.

The mineral substances on which these complex decomposition and leaching processes operate are themselves very varied and in consequence the range of variety of soils is considerable.

Classification is, however, rendered practicable by the circumstance that the redistribution of the products of decomposition and the effects of leaching lead to changes in the appearance of the successive layers of soil as one goes downwards. The top layer is darkened by the organic matter left by the vegetation: the lower layers vary in colour and physical condition according as they represent zones of loss of material or of deposition. A profile is thus developed

[1] W. Noll, *N. Jahrb. f. Min.*, Abt. A, 1935, **70**, 65; *Chemie der Erde*, 1936, **10**, 129. See p. 172.

[2] B. B. Polynov, *Proc. Dokuchaev Soil Committee*, 1915, No. 2; A. E. Fersman, *Geochemistry of Russia*, 1922, Part 1, 189.

[3] S. Mattson, *Soil Sci.*, 1932, **34**, 209-240.

[4] Fuller accounts of soil classification are given in G. W. Robinson, *Soils, Their Origin, Classification and Constitution*, 2nd ed., 1936, Murby. A short but good account is given in *Imp. Bur. Soil Sci. Tech. Comm.* 29, 1934.

which records the history of the soil: these profiles form the basis of the morphological classification of soils which has been widely adopted. It is, however, now recognised that the account of the soil is not complete without adequate chemical examination of the successive layers. The actual appearance of the profile depends very much on the extent to which the iron has moved, but this is not an adequate measure of the leaching process.[1] Further, the same general appearance of the profile may be associated with important differences in the chemical composition. Chemical characteristics are therefore now taken into account; while this has made for greater accuracy it has also added a number of complications and it has raised up many problems that have not yet been solved.

The method of classification based on profile study was first developed in Russia by Dokuchaev (1883) and his successors, Sibirtzev,[2] Glinka (1931) and others. A sequence of profile types was observed in passing from the north to the south-east, and these soil zones corresponded with climatic zones as shown in Fig. 30. It was therefore assumed that for each type of climate there exists a stable equilibrium soil type and that given sufficient time the climate determines the soil type. Apparent exceptions were often explained by assuming a change of climate. On this basis climate maps and soil maps were interchangeable. Glinka published a forecast of the soils of Australia, and Shantz and Marbut (1913) one of the soils of Africa, in the latter case checking the map, however, by means of a few well-chosen samples taken by Shantz.

Later work has shown, however, that the effect of water movements in the soil is so pronounced as to cut across this simple generalisation. Nearly all soil types may occur in any

[1] O. A. Grabovskaia and A. A. Rode, *Trans. Dokuchaev Soil Inst.*, 1934, **10**, 31.

[2] See N. M. Tulaikov, *J. Agric. Sci.*, 1908, **3**, 80, for an account of Sibirtzev's classification.

one geomorphological region.[1] On the highest part of the divide, where drainage is complete and no water can come in from soil elsewhere, the bases are completely leached and acid soils are possible. Lower down, enrichment of the subsoil occurs as the result of seepage from above; while still lower there may be accumulation of basic material or deposits of calcium carbonate.[2]

A further objection to the purely climatic basis was that it left out of account the differences in chemical composition of the original rock, which, however, profoundly affect the properties of the resulting soils.

The purely climatic basis for soil classification has therefore been given up and instead the full description of the profile, including its chemical composition, is used. The profile records the history of the soil and as such forms the basis of modern classification.[3] Good examples of modern treatment are to be found in the series of papers on the soils of Great Britain published for the International Congress of Soil Science at Oxford.[4]

Soil classification is not as clear cut as the classification of plants or animals. There is nothing corresponding to a genus with its sharp limits that enable an expert to place individuals definitely and incontrovertibly into one or the other group. Every soil has something of the character of every other, and the classification is based only on the relative preponderance of one process over the other. The grouping adopted here is as follows :—

[1] For a full discussion see B. B. Polynov in *Studies in the Genesis and Geography of Soils*, 1935, p. 19. Soils that occurred out of the region where they were expected on climatic grounds were called "intrazonal" by the older workers.

[2] For studies of some of these sequences in Africa see G. Milne, *Soil Res.*, 1935, **4**, 183; *Trans. 3rd Int. Cong. Soil Sci.*, 1935, **1**, 266, 270, 345. He calls them "catenas."

[3] For de 'Sigmond's system see *Soil Research*, 1933, **3**, 103; and *Trans. 3rd Int. Cong. Soil Sci.*, 1935, **2**, 49.

[4] In consecutive numbers of *Emp. J. Expt. Agric.*, 1934, 1935.

A. Weathering incomplete: much silica left. Siliceous soils.[1]

I. Free vertical drainage. Little if any calcium carbonate, so that the humus becomes acid, liberating organic acids which dissolve the sesquioxides.

(1) Podzols and podzolised soils, in the following conditions:—

(*a*) Much quartz to form a resistant framework permitting of good pore space and therefore free drainage.

(*b*) Low reserves of basic material.

(*c*) Little return of basic material by plants and earthworms.

(2) Brown earths if the above conditions are not fulfilled.

II. Good drainage. Calcium carbonate present. Humus remains neutral: little or no solution of sesquioxides. Seepage water neutral and containing calcium bicarbonate in solution. Considerable return of basic material by vegetation.

1. Brown earth.
2. Chernozem (humus layer deep).
3. Rendzina.
4. Terra rossa.

III. Drainage impeded for considerable part of the year. Ground water soils, meadow soils, peats, gleys.

IV. Little or no leaching: little humus.

1. Chestnut soils.
2. Desert soils.
3. Saline soils or Solonchak.

V. Seepage of water through saline soils.

1. Solonetz.
2. Solod.

B. Weathering more complete: much less silica.

1. Laterites.
2. Lateritic soils, red earths.

[1] Called Siallitic soils by Harrassowitz, *Trans. II. Comm. Int. Soc. Soil Sci.*, Copenhagen, A, 1933, 135.

Fig. 30 shows the sequence of these soil types in Russia, and their general relations to humus, calcium carbonate, and calcium sulphate.

Podzols.

These are formed when leaching is the predominant action in the soil. The essential conditions are :—

(1) Parent material containing neither limestone, dolomite nor possibly basic igneous rocks in any important quantity.

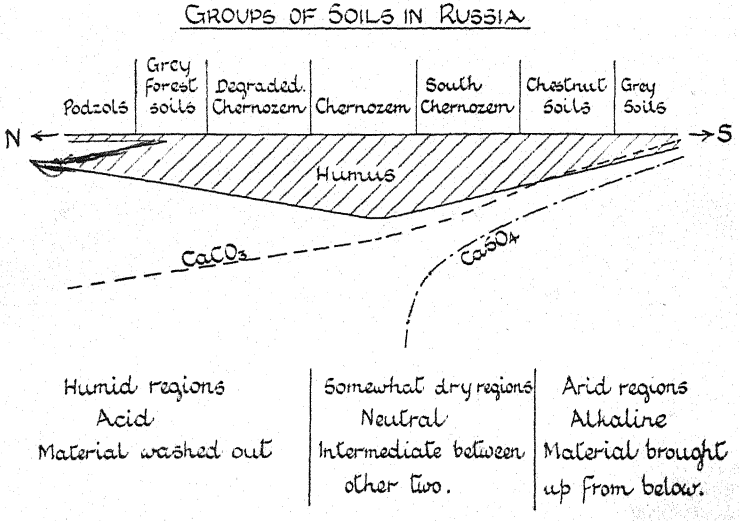


FIG. 30.—Diagrammatic representation of the distribution of soil types in Russia, from the north to the south (S. S. Neustruev).

(2) Little or no return of soluble material to the surface by the action of plants and earthworms.

(3) Sufficient excess of rainfall over evaporation to leach out basic material, and so permit the necessary acid humus to be formed and to persist.

(4) Sufficient highly resistant material such as quartz in the soil to serve as a framework providing pore spaces through which percolation can go on.

The second of these conditions is met where the vegetation consists of heaths and conifers whose narrow leaves contain relatively little mineral matter and are not much shed in winter, and also where it is sparse and consists largely of lichens and shallow rooted plants, as on the poor dry sands of the Eastern counties. In these soils earthworms are not common, owing probably to the prevailing acidity.

Most of the European podzols are found in the cool regions of the North. The temperature and rainfall conditions are very suitable, and the effect of the glacial period was to leave vast areas of permeable soils, consisting of coarse resistant particles, chiefly quartz, in which leaching proceeded rapidly. Podzols were therefore at first regarded as characteristically products of the cold North. It is now known, however, that they can arise anywhere, even in the subtropics and the tropics, so long as the necessary acid humus can remain undecomposed long enough to effect the changes.

Podzol Profile.—The typical podzol profile, developed on sandy soils either under coniferous forest or heath, has a banded appearance. The upper layer, brown to black in colour, is usually called the A_0 horizon [1] or sometimes "mor." It consists of a mass of partially rotted organic matter or "raw humus" which has lost much of its naturally low content of bases and so is very acid. The next layers are called A_1 and A_2; of these the upper, A_1, when it appears, is distinguished by a higher content of organic matter than the lower.[2] But it frequently does not appear; it is, for example, characteristically absent from the podzols of the northern provinces of Russia,[3] and Muir did not always find it in the Teind-

[1] Some workers are now giving up the use of letters. For "mor" or "duff," as it used to be called, see p. 290.

[2] For detailed examination of the humus in the different horizons see A. Schmuziger, *Diss. Eid. Tech. Hochschule*, Zurich, 1935 (Podzols, Brown earths, Rendzinas).

[3] K. D. Glinka, *Soil Science*, 4th ed., 1931. J. S. Joffe and C. W. Watson (*Soil Sci.*, 1933, **35**, 313) describe podzols in New Jersey in which the A_2 horizon is well developed, but the A_0 horizon is practically absent.

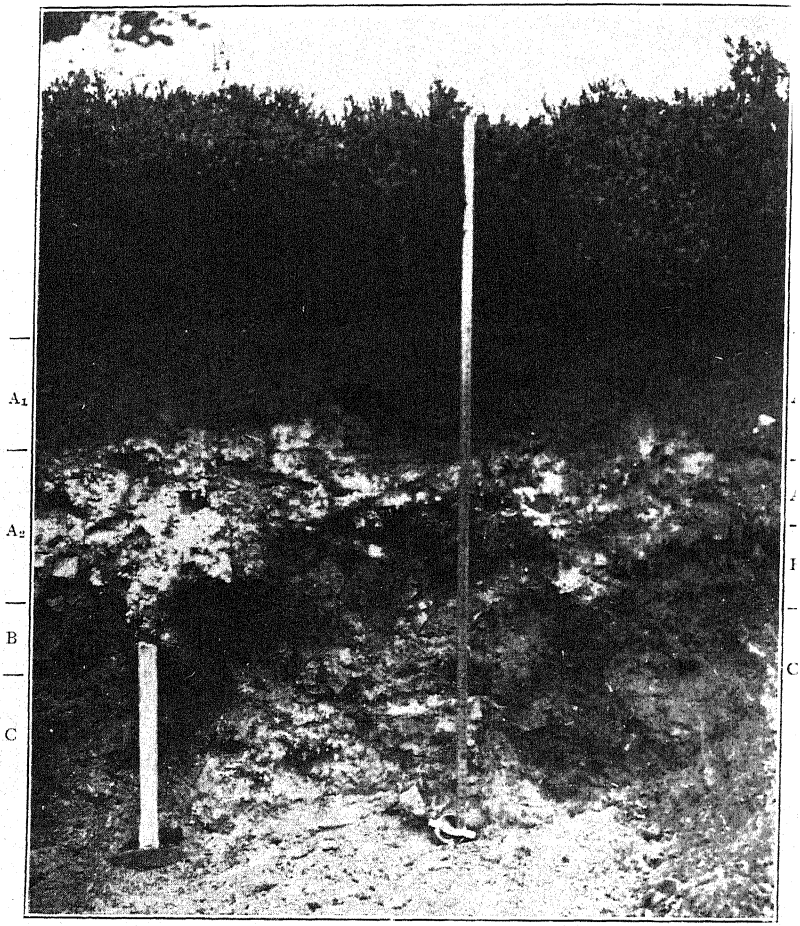


FIG. 31. Moderately podzolised sandy soil, on Lower Greensand (Hythe Beds). Blackdown Hill, Hazlemere, England.

Vegetation, Calluna, with some Erica, Vaccinium, Ulex, Pteris, Pinns and Betula. A_0 horizon (raw humus) poorly developed or absent; A_1 horizon (dark grey) well developed, 20 cm. thick; A_2 horizon (white) clearly developed but of uneven thickness (5-30 cm.); B horizon (dark brownish grey), a wavy band stained with humus (5-30 cm.); no hard pan. C, yellowish brown parent material, sand and sandstone.

(Length of scale, 100 cm.)

land profiles. The lower part, A_2, is usually lighter in colour than the soil above and below it; it tends to be grey because the iron minerals are removed, and it forms thin layers of lamellæ when dry; this platey structure is especially common in podzols formed from clays or loams. In the Russian podzols this layer often contains small concretions of iron oxide. This group of horizons, having lost material by leaching, is called "eluvial."

Below A_2 comes the B horizon, a darker zone containing some of the products of decomposition from the upper horizon. This is the zone of enrichment, or the "illuvial" horizon; it may be confined to a narrow layer forming a definite band, or it may be spread over a wide belt of the subsoil appearing rather as a stain than as a layer.

Below this comes the C horizon, of more or less unaltered parent material (Fig. 31).

Classification of Podzols.

Since the words "podzol" and "podzolised" were introduced into the literature of soil science a considerable amount of confusion has arisen as to their precise meaning. V. V. Gemmerling [1] sets out the Russian usage as follows:—

(1) *Invisibly Podzolised or Turfy Soils.*—Here the process has gone on so slightly as to be invisible to the eye; it is detectable only by chemical analysis.

(2) *Slightly Podzolised Soils.*—Here the change has gone only so far as to produce bleached spots or narrow bands. This is the usual appearance on heavy soils. The upper part of the profile is rarely well developed; there may be a slight lightening of colour under the A_0 layer, but the regions of accumulations usually occur as films on the soil crumbs or as small isolated concretions in the unaltered parent clay.

[1] Guide Book for the Excursion, *2nd Int. Cong. Soil Sci.*, Leningrad, 1930, **2**, 40. See also S. S. Neustruev, *Genesis of Soils* (in Russian Pedological Investigations, Leningrad, 1927, prepared for the *1st Int. Cong.*, Washington, 1927.

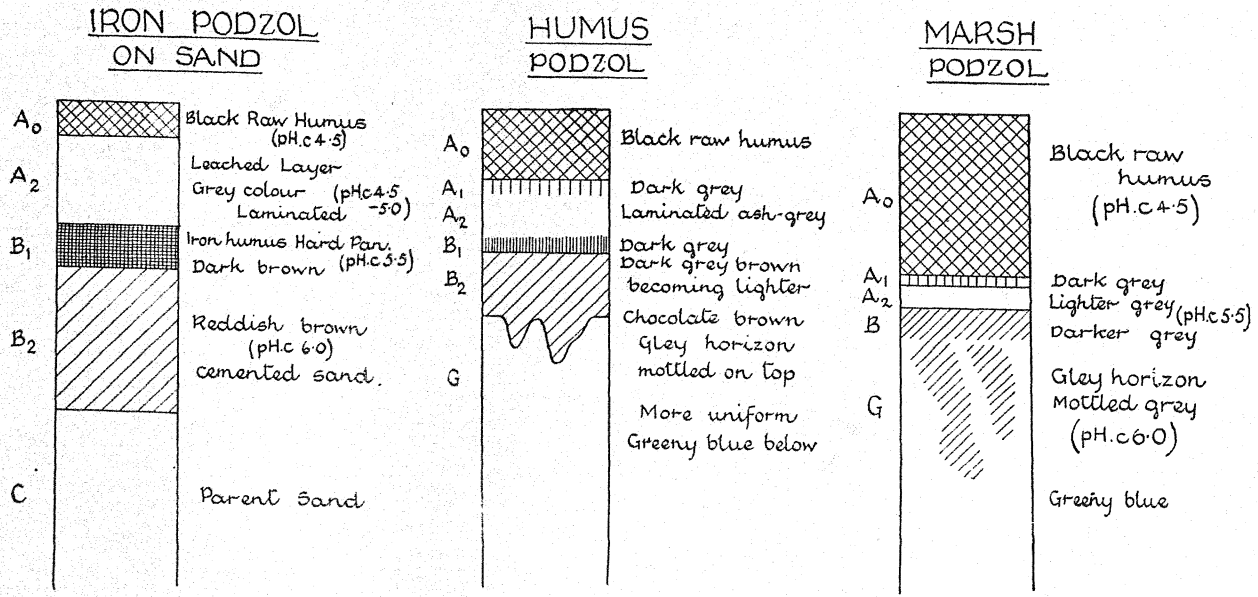


FIG. 32.—Diagrammatic sketches of podzol profiles.

(3) *Medium or Strongly Podzolised Soils.*—A definite grey or white layer has appeared.

(4) *Podzol.*—The humus horizon A_1 is very narrow or absent; the whitish horizon A_2 is very near the surface and is fairly thick.

Iron Podzols and Humus Podzols.—Variations in the amount of humus are responsible for two types of podzol much studied in Finland and the Scandinavian countries: the iron podzols, formed where sufficient humus is present for these various reactions, but no excess; and the humus podzols, formed where considerable humus is present, and the processes are therefore modified. These were first studied by Frosterus (1914). The iron podzols develop on porous, well-drained soils containing but little humus, the water level remaining well below the surface. In these podzols the A_0 horizon is relatively thin, not exceeding 8 cm.; the A_2 is fairly thick, especially on sandy soils, and the B horizon, which is reddish-brown, does not contain more than about 3 per cent. of humus. In sandy soils a very hard dark brown pan may develop on the top of the B horizon, consisting of sand particles cemented together by the iron and humus that have been washed down. If, on the other hand, the soil is not well drained, or if the ground water level is near the surface during some of the year (though not for the whole year) the "humus podzol" of Frosterus is developed. The surface layer of humus is thicker—it may be as much as 20 cm. thick—and the A_2 horizon is grey, but contains much humus which has percolated from above and deposited there. The lower part appears to the eye to belong to the B horizon, though chemical analysis shows that it really does not. The B horizon is dark brown and sometimes black on the top, due to the large amount of humus present [1] (Fig. 32).

As the peat thickens on the top, the A_2 horizon becomes darker, and the B horizon less distinct, while the amount of

[1] See also A. Pronevich, Glinka Memorial Volume, *Leningrad Agric. Instit.*, 1928, p. 163.

leaching is reduced. If the peat is more than 50 cm. thick, leaching may not take place at all.

Thus the influence of humus is very marked :—

(*a*) With small quantities of humus the process is relatively slow, and results in an " iron podzol " ;

(*b*) With more humus the process is more rapid, but the final result is much the same ;

(*c*) With still more humus a rather different type is produced, the " humus podzol " ;

(*d*) With still more humus there may be no leaching and therefore no podzol formation at all.

These humus podzols are called gley podzols by the Russians. Muir describes one in the Teindland State forest.[1]

Initial Stages in the Formation of Podzols.

Tamm [2] studied the details of some ten podzols of different ages in the forests of North Sweden. He finds that the rate of podzolisation depends not on the forest but on the undergrowth.[3]

It is most rapid under the Myrtillus association (*M. nigra*, etc.), slower under the Vaccinium association (*V. vitis-idæa*, etc.) and *Oxalis acetosella* association, and slowest under Calluna associations, though these results are complicated by the fact that the Myrtillus and Oxalis associations typically occurred on the fine sands and loams, while the Vaccinium and Calluna associations occurred on the coarser sands ; thus podzolisation tends to proceed faster on fine sands and loams than on coarse sands. The type of humus, and the quantity of fine particles that can be rapidly decomposed, both affect the rate of podzolisation

The first sign of podzolisation is the appearance under the humus (A_0) layer of a greyish leached strip (A_2) very

[1] *Forestry*, 1934, 8, 25. [2] *Medd. Skogsförsöksanst.*, 1920, **17**, 49.

[3] Since the intensity of podzolisation also affects the value of the soil for forestry, the result has an obvious bearing on the use by foresters of undergrowth as the best means of evaluating forest land.

irregular, often barely distinguishable, and about 0·5 to 1 cm. thick. This bleaching is very superficial, and hardly affects the chemical composition of the horizon. The leached out material is deposited immediately below in a layer (B_1), which from the outset is much thicker (5 to 10 cm. or more). The deposition may be uniform, but it is more usually in spots and patches which, however, join up ultimately to a continuous layer. The important difference is that the leaching out proceeds by thin layers [1] while the deposition is spread over a wider layer. As leaching continues the leached A_2 layer widens and it invades the B_1 layer; thus B_1 is first a layer of deposition then of dissolution.

The process is fairly rapid. In some of the podzols on the shores of Lake Ragunda in Sweden, the grey layer had attained a thickness of over 1 cm. in many places within the last 100 years, though even under Myrtillus between 1000 to 1500 years were apparently needed for the full development of the podzol profile. Muir [2] records the formation of a layer of 0·5 cm. thickness within the last twenty years in Kincardineshire, Scotland.

Chemical Composition of the Profile.

In passing down the profile there is a fairly definite sequence of *p*H values. On the surface of the A_0 horizon the *p*H is always low, falling below 4 in extreme cases. The general tendency is for the *p*H to rise with increasing depth, but often the A_1 and A_2 horizons are more acid than the A_0. The B horizon is rarely more acid than *p*H 4·7.

The exchange capacity of the A_0 horizon is always high, through the presence of organic matter, and it may hold appreciable quantities of exchangeable calcium in spite of its acidity (Table 51). The exchange capacity falls markedly in

[1] This gives a curious laminated appearance which enables leaching to be readily recognised. The upper surface of a lamina is usually lighter in colour than the lower, and shows the glistening particles of quartz.

[2] *Forestry*, 1934, 8, 25.

the A_1 and A_2 horizons, although the percentage saturation of the soil may be increasing; it rises again in the B horizon while the percentage saturation continues to rise (Table 50).

TABLE 50.—THE AMOUNT OF EXCHANGEABLE BASES PRESENT IN A PODZOL PROFILE. GEDROIZ (1927).

Depth of Sample in Cm.	Absorption Capacity in Milligram Equivalents per 100 Grm. of Soil.	Percentage Composition of Exchangeable Bases.		
		Ca.	Mg.	H.
10–15	12·1	13·9	7·5	78·5
15–20	4·6	20·8	8·4	70·8
20–25	1·8	40·5	20·1	39·4
30–35	4·3	50·1	43·7	6·2
50–55	11·9	49·5	46·9	3·6
100–105	12·4	54·6	41·5	3·9

Podzols in Great Britain have been studied by A. Muir of the Macaulay Research Institute, Aberdeen, G. W. Robinson of Bangor, W. Morley Davies and others. Table 51 shows the composition of the various horizons of a profile in the Teindland State Forest.[1]

The ultimate analysis shows the considerable loss of aluminium and iron oxides from the A horizon and their accumulation in the B horizon, the aluminium as usual penetrating somewhat further down than the iron. The silica decreases in the B horizon as the result of the increase in the sesquioxides. The analysis of the clay shows the same general features, but with differences in detail that deserve further investigation. The alumina in the clay reaches its maximum in the B_2 horizon, while in the soil this occurs in B_3. On the other hand the iron in the clay is at a maximum in the B_3 horizon, but in the soil this occurs in the B_2 horizon. The *p*H steadily increases in going down the profile, attaining, as in many other cases, values ranging about 4·7 in the lower part of the B horizon; the very small amounts of exchangeable

[1] A. Muir, *Forestry*, 1934, 8, 25.

TABLE 51.—ANALYSIS OF THE VARIOUS HORIZONS OF A PODZOL PROFILE IN TEINDLAND STATE FOREST. A. MUIR.

(A) Ultimate analysis as percentage of ignited fine earth (< 2 mm.).

Horizon	A_1. 5–7 cm.	A_2. 7–14 cm.	B_1. 14–16 cm.	B_2. 16–26 cm.	B_3. 26–50 cm.	C. 60–70 cm.
SiO_2	89·43	91·05	82·49	78·86	76·40	83·12
TiO_2	0·14	0·12	0·24	0·21	0·21	0·11
Al_2O_3	6·11	5·81	10·10	10·30	11·08	8·56
Fe_2O_3	0·89	0·55	2·71	3·59	3·32	2·19
CaO	0·63	0·45	0·52	0·68	0·94	0·59
MgO	0·30	0·54	0·40	0·22	0·71	0·46
Undetermined residue [1]	2·50	1·78	3·54	6·14	7·34	4·87
Total	100·00	100·00	100·00	100·00	100·00	100·00
Loss on ignition	38·73	1·77	7·87	5·66	3·92	1·63
Moisture (105°)	12·02	0·65	5·41	4·72	4·12	1·46

(B) Analysis of clay fraction: as percentage of ignited clay.

Horizon	A_2. 7–14 cm.	B_1. 14–16 cm.	B_2. 16–26 cm.	B_3. 30–40 cm.	C. 60–70 cm.
SiO_2	59·02	46·28	31·73	33·80	35·20
TiO_2	3·59	1·19	1·82	1·50	1·00
Al_2O_3	24·20	29·92	38·36	31·62	24·56
Fe_2O_3	4·18	14·36	20·42	21·71	18·80
SiO_2/R_2O_3	3·71	2·00	0·95	1·26	1·63
SiO_2/Al_2O_3	4·12	2·61	1·03	1·80	1·92
Al_2O_3/Fe_2O_3	9·09	3·28	4·01	2·30	2·59

(C) Absorbed bases and *p*H value.

Horizon	A_0.	A_1.	A_2.	B_1.	B_2.	B_3.	C.
m. eq. Calcium	7·0	3·0	0·8	1·1	0·5	0·8	0·8
m. eq. Magnesium	n.d.	2·6	1·0	1·0	0·9	0·8	0·8
m. eq. Hydrogen	n.d.	46·2	1·6	23·1	12·2	6·9	2·9
*p*H	3·75	3·92	4·34	4·48	4·54	4·83	5·15

[1] Probably chiefly K_2O and Na_2O.

calcium and magnesium indicate that hydrogen is probably the predominant ion in the absorption complex.

Table 52 gives an example of a podzol in Shropshire examined by W. Morley Davies and G. Owen.

TABLE 52.—COMPOSITION OF THE VARIOUS HORIZONS OF A PODZOL IN SHROPSHIRE. W. MORLEY DAVIES AND G. OWEN.[1]

	A_0. (6–9 in.)	A_1. (9–19 in.)	B_1. (19–23 in.)	B_2. (23–35 in.)	C. (Below 35 in.)
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Coarse sand	41·0	64·4	50·6	70·7	73·5
Fine sand	21·9	22·0	12·5	20·6	17·5
Silt	9·6	7·6	6·9	1·8	4·2
Clay	2·7	1·3	8·8	2·2	3·3
$CaCO_3$					
Loss on solution	1·43	0·45	2·6	1·54	0·15
Moisture	3·54	0·67	3·5	1·52	0·90
Loss on ignition	25·05	3·04	15·55	2·68	1·58
C	14·88	1·63	17·14	0·40	0·04
C/N ratio	29·24	13·36	23·48	5·76	1·43
*p*H	3·70	3·13	3·73	4·75	4·75
Exchangeable Ca mgm. eq. per 100 grm.	1·57	0·50	0·75	0·21	1·53
Composition of the clay fraction.					
SiO_2	52·62	54·61	44·78	38·54	46·85
Fe_2O_3	10·10	2·89	5·18	16·45	9·97
Al_2O_3	28·51	33·05	42·54	40·00	34·63
TiO_2	1·34	2·21	2·06	0·85	0·43
SiO_2/R_2O_3	2·55	2·66	1·66	1·19	1·94
SiO_2/Al_2O_3	3·13	2·30	1·79	1·51	2·29
Al_2O_3/Fe_2O_3	4·42	21·82	12·85	3·81	5·46

The horizons are described as follows :—

Bunter pebble beds ; flat country ; free drainage ; heath vegetation.

A_0	0-6 in.	Leaf mould.
	6-9 in.	Greyish-black, humified organic matter. Bleached sand grains, numerous pebbles.
A_1	9-19 in.	Pale grey, loose sand with bleached grains. Numerous pebbles free from iron-oxide stain.
B_1	19-23 in.	Compact humified organic matter.
B_2	23-35 in.	Compact cinnamon-yellow light sand with numerous stained pebbles. Decreasing intensity of coloration with depth. Upper surface consists of a ¼-in. layer of cemented and lustrous iron oxide.
C	Below 35 in.	Pebbly brownish-red laminated and friable sandy rock.

[1] *Emp. J. Expt. Agric.*, 1935, **3**, 13.

The Process of Polarization.

It was formerly supposed that podzolisation required the simultaneous action of two different processes :—

(1) The mobilisation of the acid humus and its downward movement in the percolation water.

(2) The hydrolysis of iron and alumina from the soil material in the acid A_2 horizon.

The iron and alumina sols protected by the acid humus moved down into the B horizon where the system was precipitated. This deposition could not easily be explained. The sol sinking to lower levels in the soil and also the dissolved electrolytes were both supposed to become more concentrated till at a certain point flocculation set in. Once this started the flocculated material increased by absorbing colloidal substances from the passing soil water. Aarnio [1] worked out this view in considerable detail, and showed that colloidal silica and humus could precipitate sols of iron and aluminium oxides.

This simple explanation is now known to be untenable. O. Tamm [2] and O. A. Grabovskaia and A. A. Rode [3] estimated the loss of the different elements from the horizons of podzols on the assumption that no quartz was lost during podzolisation. In the A horizons the loss of alumina and silica from aluminosilicates is about the same, while the loss of iron and the alkaline earth hydroxides is definitely higher. The loss of alkali hydroxides is usually low as they occur in the more resistant felspars.

[1] *Geolog. Komm. Finland Geotekniska Medd.*, 1915, **16**, also *Pedology* (in Russian), 1915, **17**, part 2. See, however, V. T. Aaltonen, *Comm. Inst. Forest. Fenniæ*, 1935, **20**, 6 (in German), and *Trans. 3rd Int. Cong. Soil Sci.*, 1935, **1**, 364, for the alternative explanation that the B horizon is filled in from the bottom, and that the initial precipitations resemble the phenomena shown in the Liesegang rings.

[2] *Medd. Skogsförsöksanst.*, 1920, **17**, 49 ; 1932, **26**, 163.

[3] *Trans. Dokuchaev Inst.*, 1934, **10**, 31. See also A. A. Rode, *ibid.*, 1933, **8**, No. 3, p. 1, and *Studies in the Genesis and Geography of Soils*, Moscow, 1935, p. 55. Rode's investigations should be studied in detail by those interested in podzolisation.

Although B is a horizon of accumulation, there is usually some loss by leaching of alkali and alkaline earth hydroxides and sometimes also of silica, alumina and iron, but the relative proportions lost depend on the ease of decomposition of the parent minerals.

Tamm estimated that the amounts of the various substances set free annually by the decompositions in the upper layer of a young podzol (about 600 years old) on river sand were :—

	Grm. per Square Metre per Annum.	Lb. per Acre per Annum.
SiO_2	5·9	53
Al_2O_3	2·2	20
Fe_2O_3	1·1	10
CaO	0·3	3
MgO	0·5	5
Na_2O	0·3	3
K_2O	0·5	5
P_2O_5	0·15	1·5

Further Tamm, K. Lundblad,[1] and others using Tamm's acid ammonium oxalate method for determining the easily soluble colloidal material, have shown that the easily soluble Si, Fe, Al attains its maximum in the B horizon (Fig. 33). This indicates that silica as well as the iron and aluminium moves down the profile.

There is no evidence that any large differential downward movement of aluminium and iron with respect to the silica of alumino-silicates occurs during podzolisation. The early workers were misled on this point by the residual accumulation of quartz in the A horizon, and they did not distinguish between the silica in quartz and in alumino-silicates.

The organic matter is no longer regarded as protecting the iron and aluminium sols from coagulation; indeed highly dispersed humic acids in the leaching water appear to hinder the movement of iron and aluminium down the

[1] *Soil Sci.*, 1934, **37**, 137.

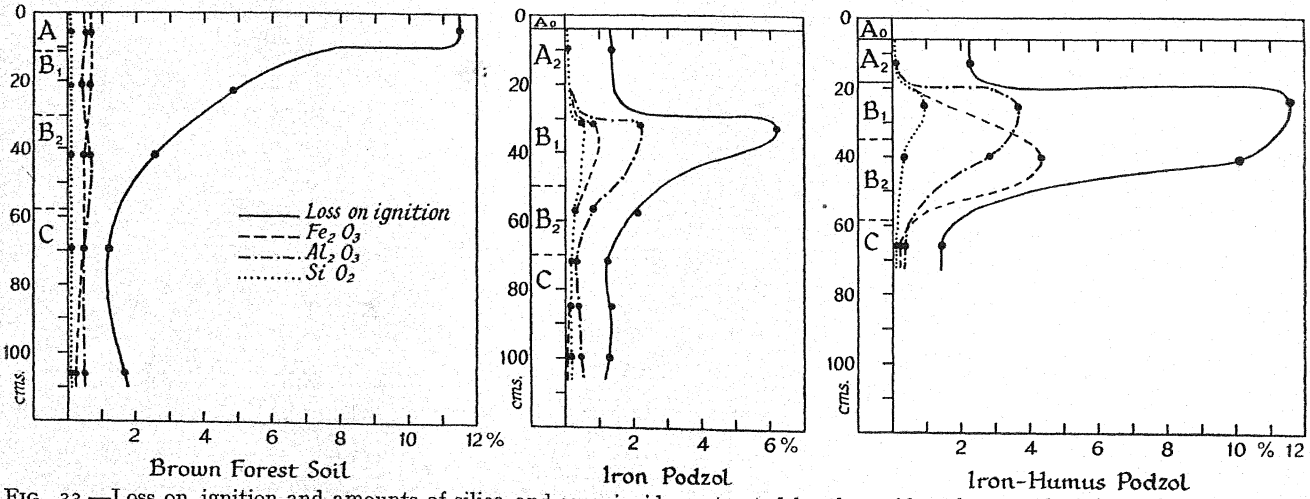


FIG. 33.—Loss on ignition and amounts of silica and sesquioxides extracted by the acid-oxalate method in a Swedish brown forest soil, iron podzol, and iron-humus podzol (Lundblad).

profile.[1] On the other hand, diffusible organic acids such as oxalic, tartaric, and citric readily hydrolyse alumino-silicates and can dissolve the products of the hydrolysis (p. 167) to form co-ordinated complexes. The modern view is therefore that the decomposing organic matter on the surface of the podzol acts by furnishing a supply of diffusible acids that can move down with the percolating water.[2] Acid humus may also move down the profile, but it does not cause the hydrolysis or transportation of the silica, alumina, and iron.

The cause of the deposition of the hydrolysed material is still an open question. Mattson[3] explains it by a hypothesis of isoelectric precipitation. The leaching of the organic acids sets up a steep *p*H gradient in the soil, the *p*H being low on the surface but higher lower down. The soil complex contains basic as well as acidic groups and it consequently functions as a base when the *p*H of the horizon falls below the isoelectric point; in the surface layer therefore it ceases to act as an acid and becomes a base with which the percolating acids can combine. If the acids form undissociated compounds with the basic groups the system remains stable, but if they form dissociated compounds with the basic groups, these groups acquire a positive charge, and are dispersed and carried down by the percolating water. These basic groups are mainly aluminium and ferric hydroxides and silicates, with an isoelectric point considerably higher than the *p*H of the percolating acids. As the complex moves downwards the *p*H of the soil rises, the basic groups come nearer their isoelectric *p*H and lose their mobility some time before it is reached. The soil acids thus become stronger in the A horizon, due to the loss of basic groups, and weaker in the B horizon, due to a gain in these groups.

[1] S. Mattson, *Lantbr. Högsk. Ann.*, 1935, **2**, 115.

[2] See H. T. Jones and J. S. Willcox, *J. Soc. Chem. Ind.*, 1929, **48**, 304T.

[3] See a series of papers by Mattson and his co-workers in *Lantbr. Högsk. Ann.*, beginning in 1934.

Some of Lundblad's [1] results with iron podzols illustrate this effect. He measured the amounts of a basic dye (methylene blue) and of an acidic dye (alizarin red R) absorbed by soils of different horizons of the profile, and he regarded the results as measuring the amounts of acidic and basic groups respectively present. The A_2 horizon acted only as an acid, the top of the B horizon had well-developed basic properties.

TABLE 53.—UPTAKE OF A BASIC AND ACIDIC DYE BY DIFFERENT HORIZONS IN PODZOLS AND A BROWN FOREST SOIL. LUNDBLAD.

(*Uptake in mgms. per gram of soil.*)

Horizon.	Brown Forest Soil.		Iron Podzol.		Iron Humus Podzol.	
	Methylene Blue.	Alizarin Red R.	Methylene Blue.	Alizarin Red R.	Methylene Blue.	Alizarin Red R.
A_2	10·85*	2·73*	2·18	0·00	3·21	0·00
B_1	4·55	1·00	2·00	0·75	3·37	1·30
B_2	3·93	0·73	0·88	0·55	4·36	0·84
C_1	1·14	0·66	0·67	0·24	2·78	0·00
C_2	1·59	0·54	0·77	0·39	—	—
C_3	—	—	0·74	0·20	—	—

* The A horizon in this profile.

PODZOLS IN TROPICAL AND SUBTROPICAL REGIONS.

Owing to the rapid destruction of organic matter in tropical soils by ants, micro-organisms, and other living things there is frequently insufficient humic acid to allow of podzolisation even when the rainfall is sufficient. Podzols are therefore less common than in colder conditions and indeed they were at first regarded as essentially non-tropical soils. Mohr [2] showed that podzolisation occurred in Java, and although Senstius [3] considered that these particular soils were not true podzols, subsequent investigation has proved beyond doubt that true podzols exist in the tropics. Wentholt

[1] *Soil Sci.*, 1936, **41**, 383.
[2] *De grond van Java en Sumatra*, Amsterdam, 1922.
[3] M. W. Senstius, *Soil Res.*, 1930, **2**, 10.

found them in Northern New Guinea [1] (Table 54), Marbut described examples found in the Amazon valley, and Vageler has also given examples. No full investigation of the course of podzolisation under tropical conditions has yet been made, however.

TABLE 54.—PODZOL FOUND BY WENTHOLT IN NORTHERN NEW GUINEA. HARDON.

	Total Soil.				Colloidal Fraction.			
	A_1.	A_2.	B_1.	B_2–C.	A_1.	A_2.	B_1.	B_2–C.
SiO_2 free (Quartz) .	22·15	6·99	3·71	4·93	—	—	—	—
SiO_2 (combined) .	37·25	44·31	35·57	34·76	46·0	46·58	34·43	33·82
Al_2O_3 . .	26·36	36·72	30·76	34·50	20·41	33·34	26·96	29·40
Fe_2O_3 (+FeO) .	2·10	2·52	21·78	18·93	1·63	2·29	19·09	16·13
CaO . .	0·49	0·26	0·25	0·21	0·38	0·24	0·22	0·18
MgO . .	0·93	0·85	0·82	0·68	0·72	0·77	0·72	0·58
SiO_2/R_2O_3 .	2·28	1·96	1·35	1·27	3·65	2·27	1·49	1·44
SiO_2/Al_2O_3 .	2·39	2·04	1·96	1·71	3·82	2·37	2·16	1·95
Al_2O_3/Fe_2O_3	19·67	22·83	2·21	2·86	19·62	22·81	2·21	2·85

	A_0.	A_1.	A_2.	B_1.	B_2–C.
Organic matter .	85·00	6·15	0·59	1·77	0·60
Nitrogen . .	0·659	0·119	0·075	0·076	0·065
*p*H . . .	3·0	4·3	3·9	4·3	5·0

Polynov, Antipov-Karataev, and Kovda have studied podzols found in the subtropical zones in Russia. There was no zone of humus enrichment in the lower horizons, either because the organic acids which effect the mobilisation of the sesquioxides are rapidly oxidised, or because in subtropical conditions the mobilisation is brought about in some other way. N. Antipov-Karataev and L. I. Prasolov,[2]

[1] The analyses were made and discussed by H. J. Hardon, *Natuurk. Tijd.*, 1934, p. 25.

[2] *Trans. Int. Soc. Soil Sci.*, Soviet Section, 5th Comm., **A1**, 1935, p. 70.

in discussing the Sochi soils, suggest that the peptisation is brought about by silicic acid.

Iron Pan Formation.

Pan (Orterde) Formation: the End of Podzolisation.

As the podzolisation process continues the B horizon receives more and more colloidal material from above till finally on sandy soils a cemented layer or pan may be formed which frequently becomes hard and impermeable to water, stopping drainage altogether.

Pan formation is so common in Northern Europe that it early attracted the attention of agricultural chemists. The older explanations were purely chemical; it was supposed that the bases were washed out as humates, the iron having first to be reduced to the ferrous state, since ferric humate is insoluble. This view was developed by C. Emeis [1] and Ad. Mayer [2] but it failed to account for many of the facts, especially in regard to the precipitation. M. Helbig [3] developed the idea that pan formation was a colloidal phenomenon: first a dispersion, then a translocation, and finally a coagulation. This is substantially the view now adopted. H. Jenny and G. D. Smith [4] have recently studied the formation of pans in coarse-grained systems such as sand or glass beads, and they find that a very resistant pan is built up by percolating an electropositive iron sol and a clay suspension alternately through the system, washing with distilled water between each percolation. But no pan is formed if the clay suspension contains much humus. This observation probably accords satisfactorily with the theory of podzolisation already developed, for clay undoubtedly moves down the profile and if, as Mattson assumes, basic sols also move down

[1] *Waldbauliche Forschungen u. Betrachtungen*, Berlin, 1875.

[2] *Landw. Vers.-Sta.*, 1903, **58**, 161.

[3] *Naturw. Ztschr. f. Forst.- u. Landw.*, 1909, **7**, 81.

[4] *Soil Sci.*, 1935, **39**, 377. See also G. D. Smith, *Missouri Agric. Expt. Sta. Res. Bull.* No. 210, 1934.

the profile, all the conditions postulated by Jenny and Smith are present.

Transformation of Podzols: Relations to Brown Earths.

The formation and persistence of podzols depends on two essential conditions :—

(1) Free drainage, *i.e.* deep water level.

(2) No return of soluble material to the surface.

When either of these conditions ceases to be satisfied the podzol undergoes a change. If the vegetation changes from the narrow leaved conifers or ericaceous plants to deciduous broad-leaved plants, bringing back more mineral matter to the surface, the podzol tends to become a brown earth. If the drainage is impeded the iron podzol changes to a humus or a marsh podzol, and if the water level remains high for long enough the podzol becomes a gley.

Effect of Impeded Drainage on the Soil Profile.

Ground Water and Gley Soils.

Important changes occur when the drainage becomes impeded as, for example, on heavy soils ; or when it ceases altogether as on soils whose ground water is near the surface for considerable periods of the year. Under these circumstances the following factors operate :—

(1) The oxygen supply in the subsoil is very poor for considerable periods of the year, so that reducing conditions set in and alter the type of vegetation.

(2) Special types of vegetation begin to develop, giving rise to peat which accumulates on the surface and further reduces the oxygen supply and the vertical drainage in the profile.

(3) The decomposition of organic matter is slowed down, and much less hydrolysis of the mineral components occurs during the period of water-logging. The products of hydrolysis

cannot move, which protects the minerals from further hydrolysis. Thus the chemical composition of this horizon is barely altered [1] and the *p*H of the soil solution tends towards neutrality, and may even be alkaline, due to the accumulation of hydrolysed bases.[2] The exchange complex is thus nearly always saturated. Further, some of the ferric iron becomes reduced to ferrous, and Zavalishin has recorded up to 20 per cent. of the total iron in the ferrous form. These ferrous compounds are not water soluble. They probably exist as hydroxides or in compounds with phosphorus and sulphur, and appear to be fairly mobile.

The Meadow Soils of temperate climates are groundwater soils; they carry a grass herbage; have a fairly deep, turfy, black upper horizon, not so rich in humus, however, as to constitute a peat; underneath this is a strongly gleyed horizon. The tropical analogue is the "vlei" soil of Africa, a black soil occurring characteristically in valley floors or depressions, in association with red soils on the higher land.[3]

Under conditions of temporary water-logging, *i.e.* when the subsoil is reasonably dry for part of the year, conditions of alternate oxidation and reduction occur in the subsoil, giving the typical gley horizon. This is sometimes a blue-grey horizon mottled with large red spots and veins, and sometimes a mottled reddish or rusty horizon with blue-grey spots and veins. This horizon is very common in the deeper layers of profiles of heavy soils. G. W. Robinson [4] has given a typical

[1] O. Tamm, *Medd. Skogsförsöksanst.*, 1932, **26**, 163.

[2] A. A. Zavalishin, Glinka Memorial Volume, Leningrad Agric. Inst., 1928, p. 45. For a full English Summary of this paper see J. S. Joffe, *Soil Sci.*, 1935, **39**, 391. The determination of *p*H by the quinhydrone electrode in the gley horizon is dangerous, since manganese compounds also tend to accumulate which make the quinhydrone electrode give high and unsteady readings.

[3] H. B. Maufe, *South African J. Sci.*, 1928, **25**, 156; D. S. Gracie, *Kenya Dept. Agr. Bull.*, 1930, No. 1; G. Milne *et al.*, *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 270.

[4] *Soils*, 2nd ed., 1936, Murby, pp. 248 and 279; *Emp. J. Expt. Agric.*, 1934, **2**, 258.

analysis of a weakly gleyed ground-water soil under grass and compared it with a better drained and somewhat higher-lying brown earth on the same farm (Table 55).

TABLE 55.—ANALYSES OF GROUND-WATER SOILS AS COMPARED WITH THE BETTER DRAINED BROWN EARTH. G. W. ROBINSON.

	Ground-water Soil.			Brown Earth.			
	0–10 in. Greyish Loam.	10–20 in. Greyish Mottled Brown Micaceous Loam.	20–30 in. Grey and Brown Mottled Micaceous Heavy Loam.	0–9 in. Dark Brown Stony Loam.	9–15 in. Brown Stony Loam.	15–36 in. Reddish Brown Stony Loam.	36–48 in. Yellowish Brown Stony Loam.
Organic carbon per cent.	3·6	0·8	1·4	2·90	2·05	1·10	0·0
Clay per cent.	20·7	15·7	14·3	18·7	20·0	16·9	—
*p*H	6·9	8·0	8·0	5·4	5·6	5·9	5·8
Clay fraction :							
SiO_2/Al_2O_3	2·50	2·63	2·66	2·39	2·47	2·41	2·64
SiO_2/R_2O_3	2·05	1·99	2·02	1·80	1·85	1·80	2·05
Al_2O_3/F_2O_3	4·53	3·11	3·15	3·05	2·99	2·95	3·47

Under cool conditions when the peat layer can become well developed, the gley horizon occurs a little way below the bottom of the peat. Tamm found a very pronounced maximum of acid-oxalate soluble iron at the top of this horizon (Fig. 34), possibly as much due to ferrous iron rising up with the ground-water as to iron mineral originally present. Zavalishin found that the ratio of magnesium to calcium in the exchangeable bases increased with depth in the gley profiles he examined, but his data are not sufficiently complete to decide if this is due to differential removal of magnesium from the upper layers or of calcium from the lower layers of the profile. If the peat layer becomes much thicker, however, percolation becomes so restricted that very little chemical change takes place and the gley horizon is no longer developed. Under these conditions Tamm showed that some organic matter can percolate into the soil, but his acid oxalate solution

dissolved very little iron from the horizons under the peat (Fig. 3v).

PAN (ORTSTEIN) UNDER WATERLOGGED CONDITIONS.

If the water table has cyclical rises and falls the gley process may begin, and a large concentration of ferrous iron may be produced at the top of the gley horizon during water-logging. In some conditions water can drain away from the

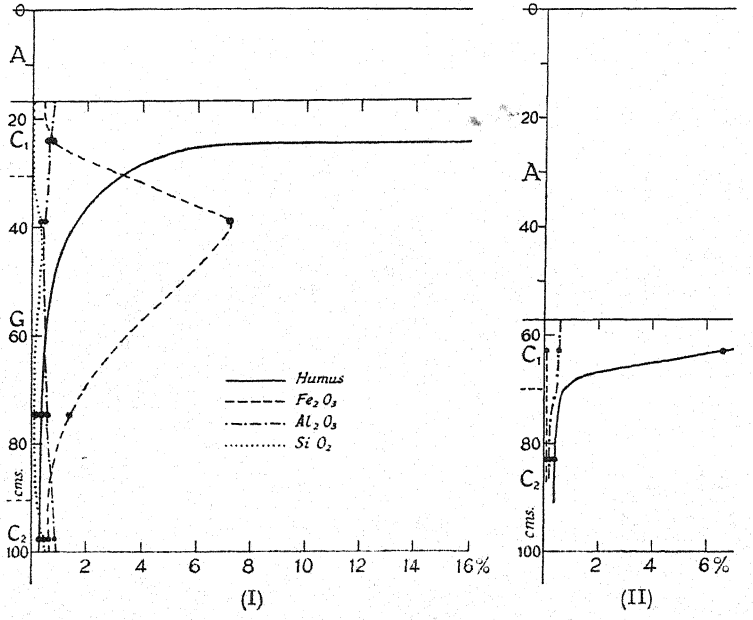


FIG. 34.—Humus content and amounts of silica and sesquioxides extracted by the acid oxalate method from a marsh profile (I) with and (II) without a gley horizon (Tamm).

coarser pores allowing the air to enter while much ferrous iron is still there. This oxidises to ferric iron which is less mobile, and tends to become more stable if the horizon is well dried before the next water-logging. Unlike the iron pan of the podzol, which is only well developed in sandy soils, this type of pan is well developed on loams and possibly also on clays in some conditions.

The Brown Earths.

The brown earths include a great variety of well-drained to moderately well-drained soils occurring in the temperate humid regions; they are common in Great Britain, Western Europe, the Eastern United States, etc. Unlike the podzols, they carry an acid to neutral mould or mull on the surface, but no peat; their profile shows no distinct horizons, and the soil complex has suffered little or no decomposition.

The brown earths are fundamentally a product of vegetation or of cultivation. The typical natural vegetation is deciduous hardwood forest, a type that reverses the effects of leaching. Plants of this kind take up from the soil a considerable amount of mineral matter, particularly Ca, Mg, K, Al, $—PO_4$ and $—SiO_4$: they transport it to their leaves from which it is released when these fall to the ground, and the minerals so liberated become available to the plants once again. The vegetation returns more than the surface had lost: it brings up material produced in the subsoil from the parent material there. Thus a dynamic equilibrium sets in, determined by the type of vegetation and the treatment of the soil. These conditions are also often favourable to earthworms which are continuously mixing the surface organic matter with the soil and bringing up material on to the surface from below (p. 253).

Brown earths are formed wherever this type of vegetation can flourish; they thus typically occur in the temperate regions on fairly well-drained medium to heavy soils derived from parent material containing sufficient reserves of base, as basic igneous rocks, acid igneous rocks not containing too much quartz, quartzite or kaolin; or reworked or sedimentary deposits not containing too much quartz. On parent material rich in quartz or quartzite the vegetation is usually heath or coniferous forest, consequently podzols are formed. On soils possessing only a small base reserve, either coniferous or deciduous forests can thrive. Under coniferous forest pod-

zolisation can proceed quite rapidly, while under deciduous forest brown earths are formed. By changing the vegetation brown earths can be transformed into podzols or podzols into brown earths.[1]

The older workers did not realise the importance of the vegetation and attributed the distribution of brown earths and podzols to climatic factors. But in Great Britain, for example, podzols are found on the warm, dry heaths of the southern and eastern counties of England and brown earths in the cooler and damper regions of Scotland.

Brown earths are also formed as the result of cultivation in the temperate regions. The cultivator is continuously mixing the surface soil, growing crops that remove the products of leaching from the lower horizons and adding fertilisers and farmyard manure on the surface.

Brown earths also occur on hill slopes in regions where podzols occur on the top of the hill and in the valley. This has been noted by numerous workers, as, for example, O. Tamm, A. Stebutt,[2] and A. Muir.[3]

The profiles of the brown earths under natural conditions show great diversity. The upper layer is acid to neutral, usually about *p*H 5-7, it is dark brown to chocolate in colour, and has only a thin layer of organic matter on the surface; otherwise the organic matter and the mineral matter are well mixed. On drying, this layer gradually lightens in colour, becoming brownish and yellowish; it cracks horizontally and vertically and often breaks up to a good crumbly structure: underneath is the decomposing rock. The profile shows no definite eluvial or illuvial horizon, though frequently there is a washing down of clay.

Table 56 gives the chemical compositions of two typical British brown earths, one from Shropshire on a sedimentary

[1] O. Tamm (*Medd. Skogsförsöksanst.*, 1921, **18**, 105, and *Svenska Skogsvardsfoseningens Tidskrift*, 1930, **1**, 1) has given examples of podzols planted with birch becoming brown earths.

[2] *Ztschr. Pflanz. Düng.*, 1930, A, **15**, 134.

[3] *Forestry*, 1935, **9**, 116.

deposit and one from Scotland on basic igneous rock. The amount of humus decreases regularly with depth and on the

TABLE 56.—COMPOSITION OF BROWN EARTHS.

(*a*) *Shropshire.*—Cultivated brown earth on Bunter Sandstone (W. Morley Davies and G. Owen).[1]

Depth (in cm.)	0–30.	30–40.	40–70.
Coarse sand . per cent.	70·9	72·5	83·1
Clay . . . ,,	1·5	1·5	1·2
C . . . ,,	1·92	0·45	0·28
N . . . ,,	0·21	0·05	0·05
C/N ratio . . .	9·16	9·88	5·60
Exchangeable Ca milli equiv. per 100 grs. . . .	9·66	6·25	4·55
*p*H	6·26	5·88	6·64
Composition of the clay fraction.			
SiO_2 . . . per cent.	48·24	49·24	48·56
Fe_2O_3 . . . ,,	10·05	10·15	10·05
Al_2O_3 . . . ,,	29·25	28·19	31·34
TiO_2 . . . ,,	0·70	0·76	0·76
SiO_2/R_2O_3 . . .	2·29	2·41	2·18
SiO_2/Al_2O_3 . . .	2·62	2·96	2·63
Al_2O_3/Fe_2O_3 . . .	4·86	4·36	4·88

(*b*) *Aberdeenshire.*—Cultivated brown earth over Gabbro (W. G. Ogg.)[2]

Layer	(1).	(2).	(3)[1].	(3)[2].	(3)[3].	(4).
Depth (in cm.)	0–25.	25–35.	50–60.	70–85.	90–100.	130–140.
*p*H	5·1	5·6	5·7	5·7	5·6	5·8
Loss on ignition	14·9	8·6	4·4	4·8	4·1	2·7
Exchangeable Ca (m. eq.)	6·6	3·4	4·3	14·1	10·4	10·8
Exchangeable Mg (m. eq.)	0·5	0·3	0·4	4·7	2·7	2·4
Exchangeable H (m. eq.)	11·9	8·4	2·3	2·6	1·8	1·3
Clay per cent.	20·9	11·2	12·9	14·3	4·8	4·1
Clay fraction:						
SiO_2/R_2O_3	1·19	1·11	1·48	1·74	1·57	1·64
SiO_2/Al_2O_3	1·63	1·46	1·93	2·41	2·13	2·23
Al_2O_3/Fe_2O_3	2·72	3·17	3·27	2·60	2·81	2·76

[1] *Emp. J. Expt. Agric.*, 1934, **2**, 13. [2] *Ibid.*, 1935, **3**, 248.

basic igneous rocks there is evidence of loss of silica from the upper layers of the profile. This is in marked contrast with the podzols, where the SiO_2/R_2O_3 ratio in the middle depths falls sharply because of the accumulation of sesquioxides.

The same result is shown by Tamm's acid oxalate extracts. Fig. 33 on page 271, due to Lundblad,[1] shows that there is little production or translocation of easily soluble mineral matter, and no horizon of accumulation. Table 53 on page 273, also due to Lundblad,[2] shows the great contrast between the podzol and the brown earth, since the brown earth shows no tendency to accumulate basic material in the lower horizons.

The interpretation of these results seems to be that in the brown earth formation there is a removal of calcium and magnesium carbonates if originally present; some removal of exchangeable bases, since the soils are acid; possibly a loss of silica; and a downward movement of organic matter, mainly due to biological causes and not to leaching.

The brown earths formed on hill slopes have somewhat different properties. Table 57, due to Muir,[3] gives a good example of brown earth on a hill slope of between 15° to 20° when the level ground is podzolised.

This soil shows no sign of podzolisation and the silica content of the clay falls continuously down the profile, but the oxalate extract shows a definite accumulation of easily soluble iron and alumina in the second layer analysed. The soil forming processes taking place under these conditions are not fully known, but the lateral movement of the soil water containing products of weathering formed on higher ground is probably an important factor.

The properties of the brown earths or brown forest soils, particularly those determining their relation to plant growth, are profoundly affected by their parent material and this covers a wide range of rocks. Three broad groups of parent

[1] *Soil Sci.*, 1934, **37**, 137. [2] *Ibid.*, 1936, 41, 383.
[3] *Forestry*, 1935, **9**, 116.

TABLE 57.—ANALYTICAL DATA FOR BROWN EARTH PROFILE. MUIR.

Depth	0–10 cm.	20–30 cm.	30–40 cm.	90–100.
*p*H	5·26	5·35	5·24	5·36
Clay, per cent.	16·25	14·87	8·87	5·85
Exchangeable Ca (m. eq.).	3·2	2·4	1·2	0·6
Exchangeable H (m. eq.).	9·7	5·9	3·6	2·4
Clay fraction:				
SiO_2/R_2O_3	1·51	1·45	1·03	0·86
SiO_2/Al_2O_3	1·93	1·92	1·59	1·16
Al_2O_3/Fe_2O_3	3·64	3·08	2·70	2·86
Acid oxalate Fe_2O_3, per cent.	0·64	3·00	0·69	0·43
Acid oxalate Al_2O_3, per cent.	0·55	1·75	0·64	0·44
Organic carbon, per cent.	2·93	1·88	0·85	0·31
Organic nitrogen, ,,	0·119	0·097	0·05	—
C/N	24·6	19·4	17·0	—

material are important: acidic rocks, basic rocks, and reworked or weathered deposits. In all, however, the influence of calcium is dominant: if sufficient is present the soils keep in good tilth, but if too much is present they tend to be poor in plant nutrients, especially potassium. Soils formed from acidic rocks, *e.g.* granite, usually contain much free quartz and are well supplied with potassium but not with lime: they may not contain much clay, however. They may be fairly deep since the granite weathers easily. These soils readily podzolise, and are better suited to spruce forests than to deciduous trees. Soils formed from basic rocks are usually better. Syenite and diabase weather to excellent soils, well supplied with lime, potash, and phosphates, on which oak and ash are typical trees. The effect of basalt depends on the size of its crystals: if these are large the soils may be deep, heavy, and neutral, carrying excellent pasture in wet regions: if they are small and compact the rock weathers only slowly and forms a thin stony soil. These soils do not readily podzolise.

Rendzina.

The process of leaching is considerably modified when the parent material is limestone or dolomite. The calcium and magnesium carbonates are washed away, leaving behind the less soluble materials laid down with them, and the resulting soils may be either—

(*a*) Red, if sufficient iron is present and the other conditions are favourable: these are called Terra rossa (p. 286) and occur largely in subtropical conditions.

(*b*) Brown earths, as found commonly in the south-eastern counties of England. The redder soils of the Oolite formation in Oxfordshire, Northants and other counties bear some slight resemblance to the Terra rossa but require more examination.

(*c*) Black soils, found commonly in Central Europe, though small patches can be seen on the top and the foot of the chalk escarpment in Bedfordshire and elsewhere: these are called Rendzinas.[1]

The rendzina consists of an upper layer (A) some 20 to 30 cms. thick, of black soil, very friable, containing many fragments of limestone or dolomite of various sizes. It rests directly on the limestone (C) from which it is sharply distinct. In the rendzinas described by L. G. Kotzmann [2] the black layer is neutral (as usual), containing 20 or 25 per cent. of organic matter, saturated to over 90 per cent. of the total exchange capacity, mostly with Ca and some Mg, thereby differing from the red soils which are usually not saturated. The exchange capacity is attributable chiefly to the humus: it varies from about 30 to 50 mg. equivalents per 100 grm. of dry soil. The clay being saturated with bases is very stable. Typical analyses are given in Table 58.

[1] A Polish peasant word meaning good, strong soil. For a description of the Hungarian rendzinas see A. A. J. de 'Sigmond, *Ztschr. Pflanz. Düng.*, 1936, 44, 24.

[2] *Trans. 3rd Int. Soil Cong.*, Oxford, 1935, 1, 296.

TABLE 58.—COMPOSITION OF RENDZINAS. KOTZMANN.

Rendzina from—	Exchangeable Bases: Percentage Composition.					Composition of Clay Fraction from Two Soils on Each Rock.				
	Ca.	Mg.	K.	Na.	H.	SiO_2, Per Cent.	Al_2O_3, Per Cent.	Fe_2O_3, Per Cent.	$\frac{SiO_2}{Al_2O_3}$.	$\frac{SiO_2}{R_2O_3}$.
*p*H 7·8 to 8·4.										
Limestone .	91	3	1·5	1·5	3	39·87	25·21	5·49	2·53	2·27
						43·14	29·32	7·13	2·45	2·15
Dolomite .	69	18	2·5	2·5	8	39·99	24·64	6·40	2·75	2·44
						43·42	27·71	8·18	2·66	2·32

The soils are fertile, but in spite of their friable condition when dry, they must not be worked when wet.

TERRA ROSSA.

This name is given to a group of red soils, rich in iron but poor in humus, found on limestone in the Mediterranean region and elsewhere. In temperate regions with normal rainfall the weathering of hard limestones gives rise, as already stated, to brown earth well supplied with humus, in which iron has tended to wash down rather than to accumulate near the surface.[1] Under conditions of high winter rainfall and hot, dry summers (as in the " Mediterranean " type of climate) however, the red colour is very pronounced, partly because there is insufficient humus in the surface soil to mask it; partly it may be, as Reifenberg has suggested, that iron rises to the surface during the summer. As a result soils are formed that resemble the red earths in physical properties and have SiO_2/Al_2O_3 ratios usually above 2. The surface layers have lost much of their basic material and so may be acid, but

[1] Sometimes the deeper cracks of the limestone contain red weathering products resembling Terra rossa.

they are by no means entirely zones of loss; even the acid soils frequently contain fragments of the hard limestone. Numerous ironstone concretions commonly occur in them, indicating an irreversible precipitation of sesquioxide gels, the movement of which, in the first instance, A. Reifenberg [1] attributes to the peptising action of silicic acid: he regards this action as one of the essential features of Terra rossa. He shows also that the Terra rossa clays have a high SiO_2/Al_2O_3 ratio but a low SiO_2/Fe_2O_3 ratio and that both are higher in soils overlying limestone than in those overlying basic rocks.[2]

Glinka made the distinction that only hard limestones yielded Terra rossa: the soft ones give Rendzinas.

Humus or Peat Soils.

Humus soils fall into two broad groups: one which has lost most of the calcium and other bases by leaching; the other which by its position not only retains its basic material but may also receive accessions brought in by seepage or surface water. The two groups differ in reaction; the first is strongly acid, the second is less so.

These two groups have very different properties.

(1) Acid humus is characterised by
- (*a*) poverty of bases,
- (*b*) slow decomposition,
- (*c*) presence of structural remains of plants.

Acid humus often occurs as a distinct and sometimes very thick layer on the surface of the mineral soil. It is then known as raw humus. It is generally derived from acid tolerant plants and trees such as heather, bilberry, pine, spruce, which contain a low proportion of bases in their ash.

[1] *Koll. Chem. Beih.*, 1929, **28**, 55; *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 306. See also A. Stebbutt (1930). This action is discussed by H. Harrassowitz, *Fortschr. Geol. Palaeont.*, 1926, **4**, 253.

[2] A. Reifenberg and S. Adler, *Ztschr. Pflanz. Düng.*, 1933, A, **30**, 345, 356.

Poor sandy soils and soils derived from acid rocks are particularly liable to become covered with deposits of raw humus, as instanced by the heather peats on the granite of Dartmoor and Cornwall.

In Germany raw humus is subdivided into "Torf" and "Auflage-humus." There is no sharp distinction between the two types, but the term "Torf" (peat) is generally confined to the more compacted types of raw humus that can be cut with a knife. "Auflage-humus" is looser and usually less acid and more fertile than Torf. Raw humus very frequently forms the A_0 horizon of heath and forest podzols.

(2) Less acid humus, or mull, is characterised by
- (*a*) the presence of more or less exchangeable calcium,
- (*b*) fairly rapid decomposition,
- (*c*) absence of structural remains of plants,
- (*d*) a crumbly structure.

It is always mixed with some mineral matter, and there is no sharp distinction between the mull layer and the top layer of the mineral soil. The term "neutral humus" is somewhat unfortunate, and is going out of use. Most mulls have distinctly acid reaction—*p*H 4·5-6·5, as compared with *p*H 3-5 of raw humus. They commonly form the surface layers of brown earths, of which the characteristic vegetation is deciduous forest.

The connection between vegetation and humus types was first fully studied by P. E. Müller[1] (1887) in a classical investigation of the soils of the Danish beech forests, in which both mull and raw humus (which he called "Torf") occurred.

On mull the characteristic plants were *Asperula odorata*, *Anenome nemorosa*, *Mercurialis perennis*, *Milium effusum*, *Melica uniflora*, *Stellaria nemorum*, and others, mosses being absent. The mull itself was only a few inches thick, and was underlain by 1 to 5 feet of loose soil, lighter in colour than

[1] For a summary of Müller's work see L.-G. Romell and S. O. Heiberg, *Ecology*, 1931, **12**, 567. The error pointed out on p. 569 has been corrected in the above statement.

mull, but poorer in organic matter; still lower came a compact but porous layer of soil. The surface of the soil was covered by a layer of leaves, twigs, etc. Earthworms were numerous throughout; their potent influence in the soil had recently been shown by Darwin (1881).

Torf differed completely. The characteristic plant was *Trientalis europœa* with the associated *Aira flexuosa* and moss, but surface vegetation was not very common. The loose layer of leaves was absent and the torf itself was so tough and compact that rain water could not readily penetrate. Below it was a layer of loose, greyish sand (Bleisand) [1] and lower still a layer of reddish soil (Roterde),[2] or else a pan (Ortstein). Practically no earthworms were found in the torf, but there were numerous moulds and fungi, *Cladosporium humifaciens* Rostrup and *Sorocybe Resinæ* Fr. being perhaps the commonest.

Müller believed that the distribution of mull or torf was determined primarily by the nature of the living organisms in the soil. Animals, especially earthworms, gave rise to mull, fungi produced torf. It is now recognised, however, that some local, and perhaps small differences in the habitat conditions lead to differences in the amounts of leaching and therefore of soil acidity. Once differences of this kind set in they are likely to continue, for acid-tolerant plants give rise to a more acid humus, and this in turn further encourages more acid-tolerant plants, and so more raw humus is produced, until ultimately a complete change has taken place in the nature of the vegetation, the humus and the underlying mineral soil profile.

Once one gets beyond this simple grouping it is difficult to carry classification further. The acid humus types are particularly troublesome; "mull" has caused less difficulty. The subject is continuously under review by the International

[1] Later called Bleichsand or Bleicherde.

[2] Later called Orterde or Eisenhorizont. This is interesting as one of the first recorded descriptions of a podzol.

Society of Soil Science, and a number of schemes have been proposed which, however, will not be discussed here. Neither ecological nor chemical methods have yet proved entirely satisfactory for subdividing the acid humus types, and the groupings are made more or less on the appearance of the material.[1]

Forest Types.

The classification of forest humus types [2] is based on simple morphological and chemical characters which can be easily observed directly in nature.

These have been much studied in Sweden by Hesselman [3] and in the United States by Romell and Heiberg: [4] both retain the word "mull" for the less acid group, but Romell and Heiberg used the word "duff" for the more acid group. Hesselman distinguishes three main types according to their acidity, namely, mull (least acid); mår or mor; and raw humus (most acid). These types tend to be more sharply separated from the underlying mineral soil, the more acid they are. Each type can be considered as made up of two more or less distinct layers:—

(1) The upper "Förmultningskikt" (F-layer, decomposition layer) consisting of plant residues that are decomposing but still possess structure;

(2) The lower "Humusämneskikt" (H-layer, humus layer) consisting of amorphous matter devoid of structure.

The F-layer is usually very thin or entirely lacking in mull and mor, and the H-layer merges gradually into the mineral soil. In raw humus the F-layer is often thick, and

[1] A. P. Dachnowski-Stokes presented a comprehensive scheme to the 3rd Int. Cong. Soil Sci., Oxford, 1935 (*Trans.*, **1**, 416).

[2] By forest humus layers is understood the top layer of the soil, owing its characteristic features largely to its content of organic matter. This part is often called A_0 or A_1.

[3] *Medd. Skogsförsökanst.*, 1926, **22**, 169-552; 1927, **23**, 337.

[4] *Ecology*, 1931, **12**, 567-608. Details of these two systems of classification were given in the last edition of *Soil Conditions* and need not be repeated here.

the H-layer is only slightly mixed with the mineral soil. Romell and Heiberg subdivide the acid types or "duff" according to origin and appearance; and the mull, according to its structure.

In the system of classification proposed by C. H. Bornebusch and S. O. Heiberg in their Report to the 3rd International Congress of Soil Science [1] two main kinds only are recognised: "mull" and "mor."

I. *Mull:* a mixture of organic matter and mineral soil, of crumbly or compact structure, the transition to lower layers not being sharp. Three forms are distinguished:—

(*a*) *Coarse mull:* [2] Coarse-grained structure, organic matter very conspicuously mixed with mineral soil (usually 5-20 per cent. organic content; in exceptional cases even considerably higher).

(*b*) *Fine mull:* Fine grain structure. Organic content high (usually over 50 per cent.).

(*c*) *Firm mull:* Dense compact structure, usually a low content of organic matter, often less than 5 per cent.

II. *Mor:* Organic matter practically unmixed with mineral soil, usually more or less matted or compacted. The transition to mineral soil is always distinct. It is often composed of two layers named (after Hesselman) [3] the F-layer, *i.e.* fermentation layer resting on the H-layer, *i.e.* humified layer.

The F-layer consists of more or less decomposed litter, still recognisable and with rather loose structure.

The H-layer consists principally of finely-divided organic matter mostly unrecognisable as to origin. Structure more or less dense.

[1] *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **3**, 260.

[2] At the Congress in Nancy of the International Union of Forest Research Organisations in 1932, the V Section adopted the name "true mull" for this form and "superficial mull" for the "fine mull."

[3] The following definitions for F- and H-layers are not exactly in accordance with Hesselman (1926).

Three kinds of mor are recognised :—

(*a*) *Granular mor:* [1] H-layer pronounced and fine granular in structure ; lower part somewhat compacted. In dry condition, it is very easily broken into fine powder when pressed by hand.

(*b*) *Greasy mor:* F-layer usually relatively little developed, often more or less fibrous. H-layer thick, compact, with a distinct greasy feel when wet, hard and brittle when dry.

(*c*) *Fibrous mor:* F-layer well developed. Both F and H layers fibrous but not compact. Many plant remains visible also in H-layer.

Moor and Fen Land Types.

These also fall into the same two large groups depending on the extent of leaching. The classical distinction is into three main groups :—

(1) Moorland : Wet conditions, flat moor ; Drier conditions, Hochmoor.

(2) Heath (Heide).

(3) Low moor (Niederungsmoor).

(1) (*a*) The flat moor or creeping peat moss [2] is formed under conditions of high humidity (*i.e.* where the temperature is low and the rainfall high). Here the tendency to form raw humus is especially pronounced. The slowly decomposing acid raw humus forms a compact, highly colloidal mass, which absorbs large quantities of water, swells up like a jelly and becomes impermeable to both air and water. The conditions become waterlogged and anaerobic, impeding the further decomposition of the humus. This therefore accumulates continuously and tends to cover the whole area ;

[1] At the Congress in Nancy the H-layers of (*a*), (*b*), and (*c*) were called " fine humus," " greasy humus," and " fibrous humus " respectively.

[2] I. M. Robertson and G. K. Fraser, *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, 1, 418.

although deeper in basins, it does not accumulate in the centre nor is it surrounded by a marginal ditch. The drainage channels flow through the area, not round it.

(*b*) The raised peat moss or Hochmoor type is formed under drier conditions: it tends to accumulate in the centre, forming a raised central area (hence its name) and its drainage is towards the outside so that it tends to be surrounded by a ditch.

The characteristic vegetation of both types includes cotton grass (*Eriophorum vaginatum*), *Scirpus cæspitosus*, and mosses, especially *Sphagnum spp.* Both types are very infertile, and may ultimately be completely dominated by highly acid conditions.

(2) Heath is formed under drier conditions. The vegetation is mainly Ericaceæ (Calluna, Erica, Vaccinium), xerophytic plants that appear to be adapted for drier localities than moorland. Nearly all the moisture of the heaths is, however, colloidally bound by the heather peat, and is thus unavailable to the vegetation, so that a condition of "physiological drought" exists, even when the moor appears to be saturated with water.

(3) Low moor is formed in wet basins: the dominant plants include *Molinia cærulea*, *Nardus stricta*, and others. Low moors often receive seepage water charged with dissolved salts from high lying regions; they are less infertile than high moors, and can usually be reclaimed by drainage for forestry and agriculture.[1] The English fen soils are reclaimed low moors.

The history of peat moors has been the subject of much study in recent years. The presence of pollen grains and other plant remains preserved in the peat through long ages, has enabled botanists to reconstruct the flora at different

[1] See C. Malmström, "Our Peat Areas from the Point of View of Forest Draining" (*Medd. Skogsförsöksanst.*, 1928, **24**, 251-272), for a discussion of the factors influencing the successful draining of peat moors.

periods, and has led to some exceedingly interesting results.[1] Ecological studies have been made by C. E. Moss.[2]

Soils Formed under Arid Conditions: Little or no Leaching.

Under arid conditions percolating rain water plays but little part in soil formation, its main action being simply to leach soluble salts from the surface to lower horizons. The primary processes are now the mechanical disintegration of soil particles by frost and wind, and the mechanical transport of these disintegrated fragments by wind and water erosion. Ground water, on the other hand, may have even more important effects on the soil profile than under humid conditions, for it can introduce salts into the upper horizons of the soil thereby causing fundamental changes.

Two main classes of soils are formed under arid conditions:

(*a*) Those where no surface water accumulates and the ground-water level lies too deep to affect the surface soil; these are the chestnut and desert soils.

(*b*) Those where the surface water accumulates, or where the ground water comes near the surface bringing with it soluble salts; these include the saline soils, alkali soils, and others.

The Chestnut and Desert Soils.

No Surface or Ground-water Action.

These soils include the grey and brown desert soils and the so-called chestnut[3] soils of the Russian workers. They

[1] For a recent study, and reference to previous work, see C. G. C. Chesters, *J. Ecology*, 1931, **19**, 46, and H. Godwin, *New Phytol.*, 1934, **33**, 278, 325.

[2] See A. G. Tansley's *Types of British Vegetation* (1911).

[3] This word has been adopted in the literature but it is misleading: it has nothing to do with the colour of the horse-chestnut but was suggested by the colour of the sweet chestnut: the colour of the soils is indeed more like that of gun-metal. For recent Russian accounts of the chestnut soils see A. M. Pankov and P. I. Shavryguin, *Trans. Dokuchaev Soil Inst.*, 1934, **9**, 205.

usually contain very little humus but much calcium carbonate, and, if the climate is sufficiently arid, calcium sulphate and even small quantities of alkali salts as well. These, however, rarely occur in the surface soil but are washed down by rain water into the subsoil, forming a horizon of salt accumulation, particularly gypsum. Calcium in general is the most abundant cation in the soil,[1] and forms a sufficient proportion of the exchangeable ions in the clay and humus complex to confer the physical and chemical properties of calcium soils, although magnesium and the alkalis may occasionally dominate. The profile is simple; it always shows some signs of leaching except in cases of extreme aridity. With moderate rainfall the surface layer varies about dark brown. The colour on going down the profile becomes more nearly that of the parent material. Calcium carbonate which has been leached from the surface accumulates in the subsoil, first as small specks or streaks, "pseudo-mycelia," then lower down in larger aggregates. The gypsum appears below the calcium carbonate horizon first as very small crystals which become larger as one goes down. As the conditions become more arid the soil profile is telescoped, and finally in very arid soils calcium carbonate and even gypsum may occur on the surface while sodium and potassium salts are present throughout the upper layer.

Detailed descriptions of these soils for Russia are given by Glinka (1931), for Hungary by de 'Sigmond,[2] and for the Sudan by Greene.[3]

The Saline Soils: Solonchaks.

Surface or Ground-water Action.

These soils are very characteristic of arid regions. They form the arid analogue of the marsh and swamp soils of the

[1] For a discussion of the effects of the calcium minerals see W. P. Kelley, *J. Agric. Sci.*, 1934, **24**, 72.

[2] A. A. J. de 'Sigmond, 1930, in *Handbuch der Bodenlehre*, edited by E. Blanck, Vol. 3, p. 294, Berlin.

[3] H. Greene, *J. Agric. Sci.*, 1928, **18**, 518.

humid regions, and are found whenever the ground-water level lies near the surface. They occur typically on the low-lying flood terraces of rivers and on the low-lying shores of lakes. The ground water contains soluble salts which it brings up as it rises by capillary action, and deposits in the upper horizons as it evaporates. Salt soils also tend to be formed in depressions, particularly saucer-shaped depressions, having no outlet for drainage water. The mean annual rainfall is small, yet when it comes it falls in torrents so that much of the water, instead of percolating deep down into the subsoil, runs off the land, washing away the soil and small quantities of soluble salts from the surface, often scoring the surface into deep gullies, and accumulates in these depressions. Here it deposits its soil, and as it evaporates deposits its salts as well, leaving a dried up salt lake. The salts commonly present in these soils are the chlorides and sulphates of sodium, potassium, calcium, and magnesium; commonly, though not always, there is sufficient sodium to impart the typical properties of the sodium soils. They can also be formed under irrigation when the drainage is restricted.

In their unaltered form they are called Solonchaks. The profile is simple and contains no horizons; the surface soil, during the dry period, contains crystals and incrustations of salts, mainly the chlorides or sulphates of sodium or calcium, though potassium and magnesium also occur. The humus content falls off regularly down the profile, there being no indication of any horizon of accumulation. In wet weather the salts tend to be uniformly distributed throughout the profile.[1] The vegetation on these soils is very restricted, few plants being able to stand both the drought and the high salt content in the water.

Under rather moister conditions the vegetation is rather more abundant and somewhat more humus is present.

When the rainfall is too high for readily soluble salts to

[1] For fuller description see I. P. Gerasimov and E. N. Ivanova, *Trans. Dokuchaev Soil Inst.*, 1934, **9**, 100.

remain near the surface, the conditions may nevertheless permit the accumulation on the surface of the soil of calcium carbonate, derived from the bicarbonate in the ground water,[1] as white powderings or incrustations which effervesce vigorously with a drop of acid. These soils are called " carbonate solonchaks."

Summary.

These various types of soil occur commonly in the semi-arid steppes of Russia and Central Asia, Western South Africa, the semi-arid zone of Australia, and the western part of the United States. The natural vegetation is poor steppe vegetation, poor either through lack of water or through an excess of salts. Where these soils are utilised at all, it is mainly for the grazing of animals, cattle and Merino sheep which can withstand the drought. In places wheat and millet can be grown. When these soils are irrigated they become exceedingly fertile so long as they are sufficiently well drained to prevent accumulation of salts, for they contain a large supply of plant nutrients. One of the great problems in the husbandry of these soils is the prevention of erosion, for owing to the small amount of organic matter present, and the usual dry state of the land, they tend to become loose and powdery, so are carried away by the strong wind and rain storms of these arid regions (p. 576).

Modified Saline Soils.

Saline soils are very sensitive to slight changes in the water movements. Thus in an almost uniform area of land a variety of different types may be found depending on small, often almost insignificant, differences in topography, the " micro-relief " as the Russian workers term it, differences in calcium carbonate or clay content or other small causes. The Russian investigators, notably Gedroiz (1926), Polynov, and Vilensky (1930), have described the various types of

[1] The process is similar to the formation of tufa, sinter and travertine.

profiles and have studied the conditions under which each type occurs.

I. The Solonetz.

When a saline soil or solonchak becomes subjected to leaching it changes considerably in character; the first stage is called a solonetz, and the process solonisation.

The change usually occurs as the result of a fall in level of the ground water or an increase in the rainfall, but a subsidiary type can also be formed in irrigated soil containing only small reserves of calcium carbonate or gypsum when the irrigating water contains appreciable quantities of sodium salts. Two extreme types of solonetz soils can be distinguished: those containing but little calcium, and those containing large quantities of calcium as carbonate or gypsum, calcium chloride and sulphate having been the predominating salts in the parent solonchak. Most solonetz soils fall intermediately between these groups. In the second group, where there is much calcium present, the soluble salts are washed into lower horizons, leaving the clay and humus saturated with calcium. The soil becomes transformed into the appropriate steppe soil, usually either a chestnut soil or a chernozem, and it is only with difficulty recognised as having arisen from a salt soil. In the other extreme, in presence of much sodium and little calcium the salts are washed down into the subsoil as before, but now the surface soil, being saturated mainly with sodium, becomes deflocculated in rain water or water containing only little soluble salts, and humus, clay and the products of decomposition of the clay in the alkaline water are carried down a little way and then deposited. The soil being deflocculated and containing much exchangeable sodium dries out into very hard crumbs which, under some conditions, break down easily to form finer crumbs and dust but do not, however, keep their shape when wet; they fall back into a sticky paste. Cultivation is, therefore, exceedingly difficult since the soil is too hard to cultivate if it is dry and too sticky

to cultivate if it is wet. Further the surface mulch does not survive rain but falls down into a paste and dries out as a hard surface pan. A somewhat similar soil arises when much magnesium is present in place of sodium.

The washing out of a sodium solonchak containing only a small amount of calcium seems to occur in three stages. The first stage is the formation of the black alkali land, so typical of some irrigated regions, the second stage is the typical solonetz soil, and the third stage the solod (p. 301). As a solonchak has its salts removed by the further lowering of the water table,[1] the easily soluble chlorides go first, then the sulphates, and finally the carbonates. In this last stage, the percolating water contains traces of calcium carbonate, and this reacts with the exchangeable sodium of the clay to give sodium carbonate,[2]

$$\text{Na clay} + \text{Ca}(\text{HCO}_3)_2 \rightleftharpoons \text{Ca clay} + \text{NaHCO}_3$$

or

$$\text{Na clay} + \text{CaCO}_3 \rightleftharpoons \text{Ca clay} + \text{Na}_2\text{CO}_3.$$

This, when mixed with the highly dispersed humus, tends to collect in hollows and when dry forms large black patches. The soil is very alkaline, it contains sodium carbonate, and is not only toxic to plant growth but is deflocculated and practically unworkable. These soils also occur under irrigation, for the irrigation water may contain sufficient sodium salts to convert a large proportion of the clay into a sodium clay, which can then react with the water giving sodium carbonate.

The second stage in the leaching of a solonchak is the conversion of the black alkali soil to the solonetz. In the typical solonetz soil as described by Gedroiz there is sufficient sodium present to keep the soil alkaline, causing it to behave as a typical

[1] See Polynov in *Studies in the Genesis and Geography of Soils.*

[2] There has been some discussion whether sodium carbonate actually exists in soil or not. The older workers assumed that it did, and Kelley and Arany agree (*Hilgardia*, 1928, **3**, 394). On the other hand, Burgess, Breazeale, and McGeorge in Arizona argue that it does not, but that NaOH is the only compound present (*Ariz. Agric. Expt. Sta. Bull.* No. 13, 307-335, 1926; *Science*, 1927, **65**, 445).

sodium clay, but not sufficient to produce any appreciable quantity of sodium carbonate. The profile becomes banded. The A_1 horizon is laminated, while the A_2 is crumbly or cloddy. The B horizon is distinct and forms a very hard grey pan which, when dry, breaks up into large vertical columns with rounded tops. These columns have originally sharp edges and a sharp top, called a " prismatic " structure by the Russians, but, as the clay is a sodium clay, the structure is not water stable, and the top edges wash away giving the rounded or " columnar " structure. Some of the percolating solution passes along the cracks formed in the columnar structure, and in percolating some of the water evaporates depositing suspended and dissolved materials as a coating on the surface of these columns, so that they readily reappear when the soil becomes dry again. These columns break up horizontally into sharp-edged lumps, roughly cubical and about the size of hazel nuts, which will not readily break into smaller units. This is the characteristic layer of the solonetz soil. A typical profile is illustrated in Fig. 35. The chemistry of the process is that the alkaline percolating water decomposes the sodium clay and washes down the sesquioxides and humus into the B horizon but leaves amorphous silica in the A horizon. Below the B horizon are the zones of accumulation of the salts, first the calcium carbonate, then the calcium sulphate, and lower the sodium salts. The ground water also may contain considerable amounts of soluble salts, rendering it unsuitable for drinking, livestock, or irrigation. The soils in the first two stages of washing out often contain small quantities of soluble salts, which when the soil is almost dry can flocculate the clay, giving a fairly good structure. The soil crumbles readily and gives the impression of being easily workable. But this structure is unstable to rain water and the soil becomes deflocculated again. If, however, irrigation water is used containing sufficient salts to keep the soil flocculated, the structure is much more stable.

These solonetz soils are very common in Western North

America: they form a considerable area in the prairies of Canada and the Western States. Many of them agree in their morphological and physical characters with those described by Gedroiz but differ in that their important exchangeable base is not sodium but magnesium.[1]

The solonetz soils occur widely in semi-arid regions and as they are black and on the surface friable they have an appearance of great fertility which has often deceived settlers. The impermeable B horizon causes great trouble to cultivators and often seriously limits yields, but perhaps their worst feature is that after they have been broken up and deprived of the protection of the natural vegetation the high winds prevalent in these regions sometimes blow away the top layer of soil thus exposing the B horizon which becomes hard by loss of water and almost polished by the abrasion of the moving dust. These bare regions constitute a serious problem to those concerned with the settlement of semi-arid regions.[2]

II. The Solod.

The last stage, when the solonetz has been exposed to prolonged leaching, is the solod of the Russians and is found, for example, in depressions of the ground where the water used to collect, or on the high river terraces which, being flood terraces just after the glacial periods, were solonchaks. The profile of a solod formed in the absence of calcium carbonate is very similar in external appearance to the podzol. The upper layer is dark coloured and foliated, the soil below is black and crumbly with many fine roots, still lower it becomes grey, then still lighter in colour as the silica deposit becomes more and more pronounced: its structure is nutty, very different from that of the solonetz.

[1] C. F. Shaw and W. P. Kelley (California), *Trans. 3rd Int. Cong. Soil Sci.*, 1935, **1**, 330; J. H. Ellis and O. G. Caldwell (Canada), *ibid.*, 348. Magnesium solonetz soils, however, are not peculiar to North America.

[2] For an account of the solonetz soils of Western North Dakota see C. E. Kellog, *Soil Sci.*, 1934, **38**, 483.

The lower depths are like those of the solonetz: first the brownish prismatic horizon with its characteristic cracks coated with humus, and, still lower, its horizons of calcium carbonate and calcium sulphate. A typical profile is shown in Fig. 35. In this process of solodisation, the percolating water continues to remove sodium and other products of decomposition from the soil complex, replacing the exchangeable sodium by hydrogen, and depositing the products of decomposition lower down. Eventually the surface soil becomes acid, though the subsoil is first neutral and still

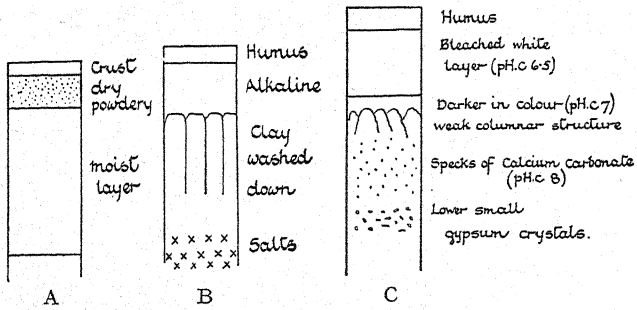


FIG. 35.—Diagrammatic profiles.

A. The solonchak.

B. The result of moderate leaching. The solonetz: round-topped columns.

C. The final result of leaching. The solod: columns irregular in shape.

lower down alkaline. The characteristic feature of these soils is the large amount of alkali-soluble silica that occurs in the top horizon.[1] Table 59, taken from Gedroiz's (1926) important paper on this process, illustrates the differences between the solonchak which has only suffered a little leaching, the non-calcium solod and the podzol on the one hand, and the calcium solod and chernozem on the other.

There is a great accumulation of amorphous silica in the non-calcium solod but not in the podzol or the calcium saturated soils. Table 59 gives the total amounts of the

[1] In the A horizon in Gedroiz's soils, but lower down in de 'Sigmond's (p. 304).

TABLE 59.—THE AMOUNT OF SILICA AND ALUMINA DISSOLVED IN 5 PER CENT. POTASSIUM HYDROXIDE FOR DIFFERENT SOIL TYPES. GEDROIZ.

Solonchak–Solonetz. (Little Leaching.)			Non-Calcium Solod. (Much Leaching: Saline Water.)			Podzol. (Much Leaching: Acid Water.)		
Depth of Sample in cms.	SiO_2.	Al_2O_3.	Depth of Sample in cms.	SiO_2.	Al_2O_3.	Depth of Sample in cms.	SiO_2.	Al_2O_3.
0-5	0·868	0·176	0-5	12·790	0·092	0-10	0·910	0·550
7-22	0·904	0·244	6-11	5·312	0·244	20-25	0·776	0·680
40-45 [1]	0·766	0·312	16-21	1·326	0·792	25-40	0·690	0·842
			40-45	1·138	0·638	50-60	0·864	1·164
			95-100	1·362	0·188	60-80	0·920	0·658
						100-120	0·914	0·786

Chernozem.			Calcium Solod.		
Depth of Sample in cms.	SiO_2.	Al_2O_3.	Depth of Sample in cms.	SiO_2.	Al_2O_3.
0-20	0·534	0·320	19-24	1·090	0·580
45-70	0·440	0·344	30-35	0·734	0·470
120-150	0·424	0·376	48-53	0·876	1·150
			175-180	0·612	0·400

[1] Salts occur.

TABLE 60.—HUNGARY. EXCHANGEABLE CATIONS. DE 'SIGMOND.

Acid Podzolised Soil. Hüvösvölgy.

Horizon.	*p*H.	Metallic Cations[1] Mgm. Equivalents per 100 grms. Soil.	Percentage of Total Cation.					HCl Extract.		
			Ca.	H.[2]	Na.	Mg.	K.	SiO_2.[3]	Al_2O_3.	Fe_2O_3.
A	5·9	14·6	13·3	57·8	1·8	18·1	6·3	8·9	3·7	1·6
B_1	5·8	16·2	20·3	52·6	3·6	15·2	6·2	9·4	4·7	2·6
B_2	6·7	18·6	29·5	48·6	3·8	9·7	7·0	10·7	7·5	3·0
C	8·1	23·30	49·6	29·2	5·1	9·7	6·4	6·1	3·0	3·4

Carbonate equivalent to 7·9 per cent. CO_2 was present in C: none in A or B.

Solod. Hortobágy Soil.

Horizon.	*p*H.	Metallic Cations[1] Mgm. Equivalents per 100 grms. Soil.	Percentage of Total Cation.					HCl Extract.		
			Ca.	H.[2]	Na.	Mg.	K.	SiO_2.[3]	Al_2O_3.	Fe_2O_3.
A	5·8	20·6	16·8	44·1	20·9	15·0	3·2	5·8	3·6	0·6
B_1	6·5	31·4	26·1	14·7	39·7	16·8	2·7	10·9	5·8	3·3
B_2	7·4	42·3	21·8	10·6	50·2	15·5	1·9	20·7	8·1	6·8
B_3	7·6	40·9	21·6	11·0	44·6	20·7	2·1	21·2	8·3	7·0
C_1	8·5	39·6	32·4	10·8	32·9	19·8	4·1	12·9	6·6	4·1
C_2	8·7	39·1	34·6	10·8	28·4	19·6	6·6	12·7	6·6	3·6
C_3	8·9	40·5	35·8	10·0	31·0	17·8	5·4	13·5	8·9	4·6
D	8·9	39·1	34·9	14·2	28·1	18·4	4·4	13·4	8·2	4·5

No carbonate present in the A or B horizons: in the C's the percentage was:

reckoned as CO_2

C_1	C_2	C_3	D
7·2	11·5	10·6	10·4

Chernozem. Csorvás.

Horizon.	*p*H.	Metallic Cations[1] Mgm. Equivalents per 100 grms. Soil.	Percentage of Total Cation.					HCl Extract.		
			Ca.	H.[2]	Na.	Mg.	K.	SiO_2.[3]	Al_2O_3.	Fe_2O_3.
A	8·0	28·2	68·1	23·5	2·2	3·4	2·8	6·0	8·3	4·9
B_1	8·2	28·8	70·7	16·2	3·2	6·2	3·7	6·0	8·1	5·0
B_2	8·7	23·7	78·4	0·0	14·7	2·7	4·4	5·4	7·0	4·6

Proceedings and Papers, First Int. Congress of Soil Science, 1927 **1**, 60.

[1] Excluding hydrogen. Hissink's S value. [2] Hissink's T-S value.
[3] Sum of HCl extract + 5 per cent. KOH extract.

TABLE 61.—SOLONETZ AND SOLOD, SASKATCHEWAN. A. H. JOEL.

Brown Plains Zone—Solonetz.

Depths.	0–3 in.	3–7 in.	7–11 in.	11–13½ in.	13½–28 in.	28–36 in.
Results expressed on moisture (105° C.), CO_2 and organic matter free basis.						
Insoluble residues .	80·6	77·2	78·0	75·9 [1]	63·3 [1]	64·6 [1]
SiO_2 soluble in base.	8·77	11·20	9·43	9·66	9·95	10·0
SiO_2 soluble in acid.	0·17	0·23	0·15	0·17	0·29	0·30
Al_2O_3 . . .	2·83	3·96	3·10	3·62	3·57	3·62
Fe_2O_3 . . .	2·44	2·98	2·83	2·72	3·22	3·41
CaO . . .	0·55	0·46	0·55	0·95	10·62	8·40
MgO . . .	0·61	0·78	1·07	0·94	3·14	4·08
Remaining results expressed on moisture free basis (105° C.).						
Organic matter .	3·10	1·58	1·19	—	—	—
CO_2 . . .	0·13	0·07	0·25	0·44	9·55	8·84
N	0·34	0·18	0·11	0·11	0·09	0·04
*p*H . . .	6·22	5·94	7·52	8·34	8·64	8·60

Brown Plains Zone—Solod.

Depths.	0–3 in.	3–7½ in.	7½–9 in.	9–13 in.	13–18 in.	18–27 in.	27–36 in.	36 in.
Results expressed on moisture (105° C.), CO_2 and organic matter free basis.								
Insoluble residue .	70·3	78·5	82·6	63·6[1]	65·2[1]	56·2[1]	55·4[1]	75·0[1]
SiO_2 soluble in base .	15·20	9·12	8·24	15·6	14·2	14·6	15·7	8·27
SiO_2 soluble in acid .	0·27	0·17	0·17	0·24	0·20	0·40	0·38	0·30
Al_2O_3 .	4·02	3·52	3·03	6·44	5·44	5·82	6·12	3·22
Fe_2O_3 .	2·66	2·20	2·14	4·21	3·44	3·67	3·83	2·78
CaO , .	0·37	0·19	0·19	0·29	1·29	6·68	4·56	3·23
MgO . .	0·61	0·49	0·51	1·34	1·73	2·34	2·19	2·10
Remaining results expressed on moisture free basis (105° C.).								
Organic matter .	5·75	3·19	2·19	—	—	—	—	—
CO_2 . .	0·11	0·00	0·00	0·11	1·26	4·22	2·61	3·02
N . .	0·24	0·11	0·10	0·09	0·06	0·06	0·05	0·03
*p*H . .	6·17	6·20	7·07	8·51	7·76	8·10	7·95	8·16
Total Salts .	0·09		0·15		0·20	3·71	—	—

[1] Results on CO_2 and moisture free basis. Organic matter not determined.

constituents of the non-calcium solod, and shows how much richer the upper horizons are in soluble silica than the lower.

Table 60 taken from de 'Sigmond (1927) shows the variation in the proportion of the exchangeable bases present in a solod in comparison with a podzol and a chernozem.

Table 61 shows the composition of a typical solonetz and solod soil in Saskatchewan.

The solods are more fertile than the solonetz soils since they do not possess the very impervious B horizon near the surface; they therefore allow better and deeper root development in the upper horizons.

Black Earths.

Chernozems.

In between the arid and the humid climates comes a great semi-arid belt found only in continental areas, where the rainfall ranges from about 10 to 22 inches per annum, but is very variable from year to year and part of it is apt to come in sudden, very heavy falls liable to cause erosion. Also it is seasonal, and not evenly distributed over the twelve months. The mean temperature is high and with it evaporation, so that the amount of leaching is low. The vegetation consists of grass along with other herbaceous plants. The climate is too dry to permit of the growth of forest, and the few self-sown trees never develop into anything more than scrub. They have no chance of becoming very old, for periodical fires and dust storms sweep the country; and the young seedling trees are liable to be devoured by the rodents that flourish there.

So long as these conditions remain, humus accumulates in the surface soil to a depth determined by the length of the plant roots; it imparts also its full black colour. There being but little leaching the bases remain in the surface so that the soil is neutral; there is no decomposition of the

clay complex or movement of the silica or sesquioxides. These soils are called chernozems. They differ from the saline soils already described in that they contain more humus, and little or no salt, so that when changing conditions render them liable to leaching they do not give rise to solonetz or solods but to soils having something of the character of brown earths or podzols.

The chernozems form a great belt running across Western Siberia, Russia, Czechoslovakia, Hungary, and in North America running north and south through Manitoba, the Dakotas, and Iowa to Kansas. Other black soils also occur in this region, and it is impossible merely by casual inspection to say which are chernozems and which are not, though the differences are clear when a profile is examined and the necessary chemical examinations made.

The parent material is, in Russia and Europe, usually loess containing much calcium carbonate: in North America it is often ultimately of glacial origin and is poorer in calcium carbonate: this leads to differences between the two sets of black earths.

In the Russian and European black earth regions the rainfall is low but the temperature is not excessive; leaching has therefore sufficed to wash out the sodium salts and the calcium sulphate, but the calcium carbonate is carried down only a short distance—three or four feet—and is then deposited as localised white incrustations forming pseudomycelium or, in the south, small patches called picturesquely by the Russians "white eyes" (bieloglaska); frequently also it is deposited on the lower side of stones or nodules. The zone of deposition is sharply defined, and can be seen at once by squirting a few drops of dilute acid down the face of a soil section. The autumn and winter "rain" comes as snow, and the early spring rain finds the clay and the humus still frozen and therefore unattackable, so these have always remained predominantly calcium combinations and therefore stable and not readily dispersible. The soil thus

remains neutral or only slightly acid. The characteristic feature of the soils is their stability: in summer the conditions are too dry for much change and in winter the ground is frozen solid, so that the colloids and the soil crumbs are alike kept intact and unaltered.

There is thus no movement of colloids from the surface into the subsoil: the profile shows a gradation from the dark surface layer containing 4 to 18 per cent. humus to the lighter layers below: there is no "B" horizon of accumulation, though the Russian workers use the term "B" for the transitional zone between A and C. The black soil does not shade off abruptly into the light coloured loess underneath; the line is wavy, and below it are frequent patches of black, called crotovines, where ancient burrows of rodents have become filled up with black earth from above (Fig. 36). The composition of the clay remains substantially the same throughout the profile: in the Nebraska chernozem for example, the SiO_2/R_2O_3 ratio was about 3·5 at each depth studied.[1]

In addition to its uniformity of appearance, the profile shows certain other characteristics. Soil taken anywhere in the upper layers crumbles easily into granules (p. 226) and completely by simple pressure in one's hand. The fine rootlets have little granules of soil attached to them so that they look rather like strings of beads. In the lower depths there is some tendency to larger grains: the lumps may be of the size of peas but not till still lower depths, if at all, is there any clear vertical or horizontal cracking into prisms or columns, and nowhere does one find the rounded columns characteristic of the soils in which sodium or magnesium dominate the properties.

[1] I. C. Brown, T. D. Rice, and H. G. Byers, *U.S.D.A. Tech. Bull.* No. 399, 1933; one of an exhaustive series of studies of the composition of clays in the United States soils. In these profiles some clay had washed down unchanged but it coagulated in the zone of salt accumulation.

TYPICAL CHERNOZEM PROFILES

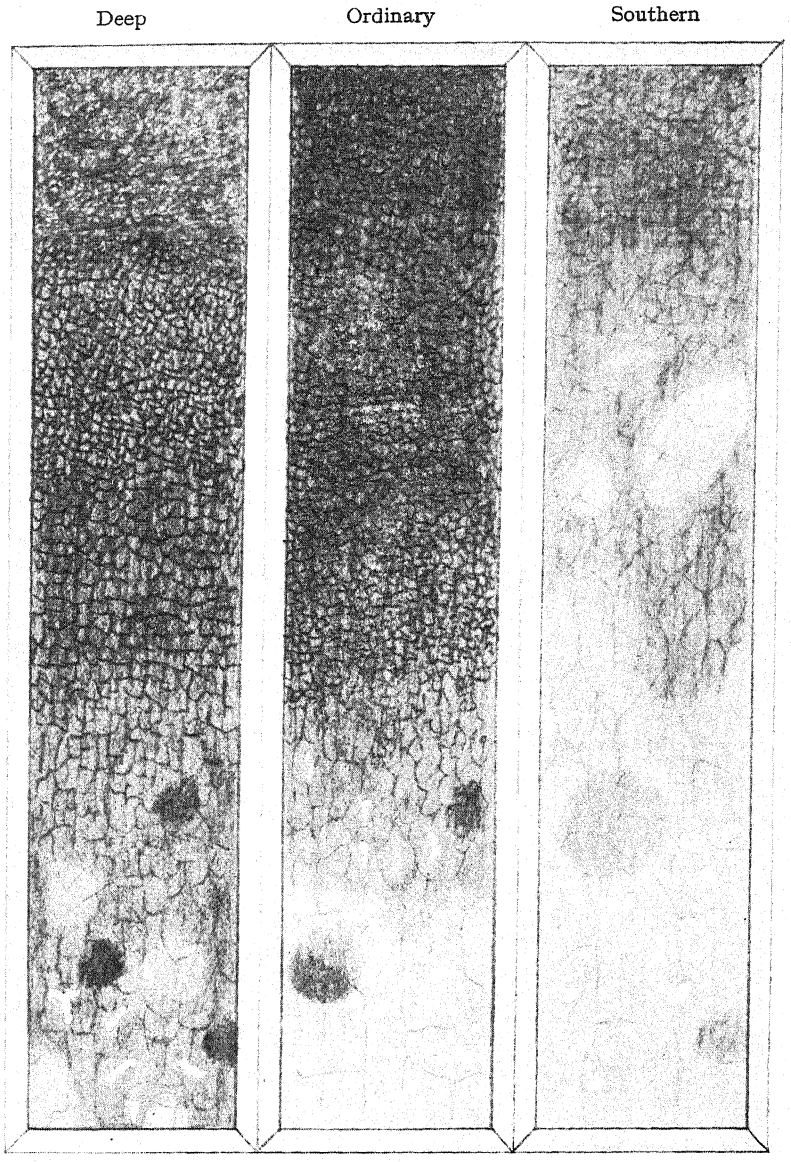
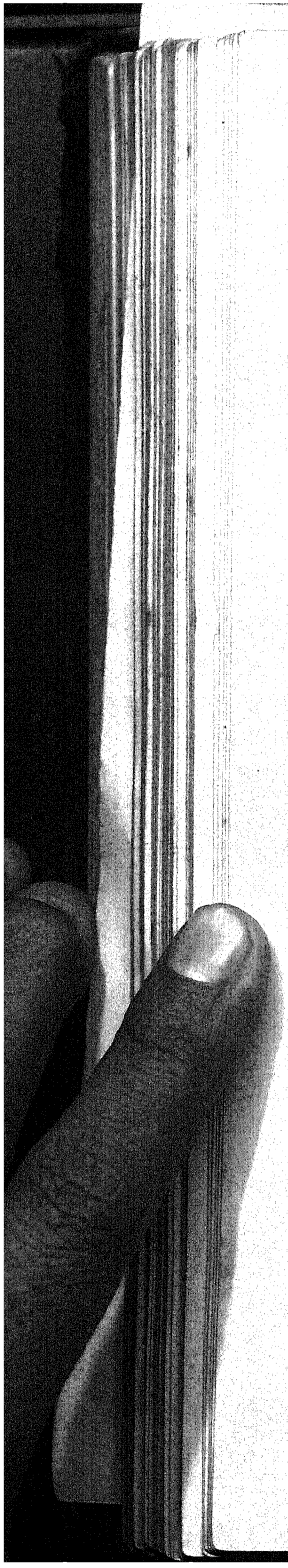


FIG. 36.

Deep Chernozem (Izberden) : granular structure (disturbed by cultivation near surface), becoming pea-like and then nutty below ; humus layer over 100 cm. in depth ; carbonate as " pseudomycelium " below about 90 cm.

Ordinary (*Medium*) *Chernozem* : granular structure ; humus layer 70-90 cm. deep ; carbonate as efflorescence or pseudomycelium below about 70 cm.

Southern Chernozem : structure less well expressed, may be granular or crumb-like near surface ; humus layer (often with chocolate-brown tint) 50-80 cm. ; carbonate as a characteristic horizon of (soft concretions) " bieloglaska" or " white eyes ' below about 70 cm.



The chemical processes responsible for the excellent structure in chernozems are not yet known. This structure is apparently only developed under grasses and similar plants; indeed G. I. Pavlov [1] and O. S. Rostovzeva and M. I. Avaeva [2] state that perennial grasses gave it to all the semi-arid and arid soils examined. Dokuchaev attributed the structure to a direct effect of the grasses but Gedroiz considered it was probably a result of well-distributed neutral organic matter. The experimental evidence is insufficient to show the relative importance of these two factors.

Degraded Chernozems.—If the grass vegetation is replaced by coniferous forests the leaching becomes intensified and the chernozem loses some of its characteristics and becomes more like a brown earth or a podzol. The soils thus formed are called Degraded Chernozems. Under coniferous forest the surface soil loses its fine granular structure and shows signs of lamination, while the lower layers show prismatic structure and break into angular lumps or nuts when dry: they are coated with a white dust of residual silica, always a sure sign of leaching. Further, signs of accumulation of iron and alumina occur in the B horizon.

Degraded chernozems occur naturally in the forest steppe soils fringing the chernozem belt; they occur also within the belt where other changes in conditions have increased the leaching, and the leaching water is not saline.

The forest steppe soils have recently been examined by A. A. Zavalishin.[3]

In the first stages of the change the humus horizon deepens and the lower limit of the horizon of base accumulation comes nearer to the surface. Later on both horizons become lifted near the surface. In still later stages podzolisation is clearly visible: the soils are dark grey and bases no longer accumulate: on the contrary the bases below the humus horizon

[1] *Trans. 2nd Int. Cong. Soil Sci.*, Moscow, 1932, **1**, 179.

[2] *Pedology*, 1935, **30**, 797.

[3] *Studies in the Genesis and Geog. of Soils*, Moscow, 1935, pp. 71-126.

are leached out. The ratio of clay in the B horizon to that in the A horizon increases. In the final stages the leaching of bases from the top becomes pronounced: the clay content of A continues to decrease: that of the B horizon decreases also if the *p*H is less than 6.

However, even the best developed podzols studied in this region by Zavalishin still contain a good deal of exchangeable calcium and magnesium in the upper layer—some 20 to 30 milli-equivalents per 100 grm. of dry soil in the top horizon.

Tropical Black Earths.—Black earths also occur in regions of higher annual temperature than that of the chernozem zone, but they differ from the chernozems in many important respects and their nature and relationships are not well understood. The *regur*, or black cotton soil of India,[1] is the best-known example; in Africa and elsewhere other black earths appear, called "black turfs," "black clays," or sometimes by analogy "black cotton soils." Some of these are not clearly distinguished from the *vlei* soils, except that their occurrence is not limited to valleys or depressions.[2]

Weathering Nearly Complete.

Laterites and Lateritic Soils.[3]

In tropical regions of high rainfall where

1. the parent material is basic igneous rock,
2. the drainage is good, and
3. the soils have long lain undisturbed,

the removal of silica has gone much further than in the soils already described: the iron, aluminium, and manganese

[1] W. H. Harrison and M. R. R. Sivan, *Mem. Dept. Agr. India, Chem. Ser.*, 1914, **2**, No. 5.

[2] B. de C. Marchand, *South Afr. J. Sci.*, 1924, **21**, 162; D. S. Gracie, *Kenya Dept. Agr. Bull.*, 1930, No. 1; G. Milne *et al.*, *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 270; C. R. van der Merwe, *ibid.*, 301.

[3] *Imp. Bur. Soil Science*, Tech. Comm. No. 24, 1932; P. Vageler, *Introduction to Tropical Soils*, Macmillan, 1933; J. B. Scrivenor, *The Geology of Malaya*, chap. 9, Macmillan, 1931.

oxides have accumulated, the iron oxide in various hydrated forms, and the alumina as gibbsite $Al_2O_3 \cdot 3H_2O$. The ratio SiO_2/R_2O_3 in the whole soil, and especially in the clay fraction, therefore falls below that obtaining in temperate climates; and beyond a certain point the soil takes on characteristic new properties and receives the special name laterite or lateritic.

The characteristic properties of laterites are as follows :—

(1) Considerable depth and freedom from iron pans, stones, or gravel—except that a few large stones may occur, but these are usually encrusted with ferric oxide.

(2) The soils are usually red, though the colour may vary from yellow to dark brown.

(3) They are fairly uniform in composition throughout their depth, and they contain much free ferric or aluminium oxide or both : their SiO_2/R_2O_3 ratio is lower than in any other soils.

(4) They show certain cultivation and ecological characteristics.

From the circumstance that laterites occur commonly in the tropics it was at first supposed that laterisation is in some way a purely tropical process requiring alkaline drainage water to dissolve the silica.[1] But it is now known that most tropical forests, under which laterite is often found, give acid humic layers and yield acid percolating water : laterites and lateritic soils have been found outside the tropics, and given suitable parent material, freedom from disturbance for a sufficient length of time, and free drainage to allow of sufficient leaching away of the silica there seems no need to involve special reactions to account for the formation of laterites. Goldschmidt[2] has described a laterisation of Norwegian labradorite under semi-Arctic conditions. Weathering somewhat resembling

[1] The difference in weathering between tropical and temperate climates is attributed by Mohr to the absence of humic acid from the soil water in tropical conditions.

[2] *Festskrift til H. Sørlie*, 27th Oct., 1928.

laterisation has been observed in Scotland,[1] and elsewhere in non-tropical conditions. An essential condition is freedom from disturbance for periods long enough to enable the processes to complete themselves. This condition is more commonly obtained in the wet tropics, where the combined heat and moisture accelerate the weathering, than in dry regions where high winds led to aerial erosion, or in cold regions where ice caps removed the existing deposits and protected the rock against weathering until comparatively recent geological times.

The name laterite is borrowed from the geologists: it is rather an unfortunate choice, as it had a geological significance which does not necessarily agree with the soil definition. The name was first used by Buchanan [2] to denote a surface deposit in Southern India, which is soft when dug, but hardens slowly on exposure, so that it forms a useful building stone. This hardening or setting is attributed to the slow dehydration of iron oxides, alumina, or alumino-silicates; no critical study, however, appears to have been made. Similar deposits were subsequently found elsewhere in the tropics. Examinations by geologists showed that these materials contain much iron oxide, and some of them much alumina, and this latter was assumed to be in the free state because the amount of silica occurring in forms other than quartz seemed insufficient to hold it as a silicate combination: the analytical methods then in use could not discriminate between free and combined alumina or between quartz and combined silica: gibbsite ($Al_2O_3 . 3H_2O$), however, could frequently be detected by petrological methods. Geologists regard ferric oxide as a characteristic constituent; if only little is present they do not use the word laterite, but call the substance bauxite or

[1] Harker, "Tertiary Igneous Rocks of Skye," *Mem. Geol. Survey*, 1904.

[2] Francis Buchanan (afterwards Hamilton), 1807: *A Journey from Madras through the Countries of Mysore, Canara, and Malabar*, 3 vols., London. This was probably not a laterite in the soil sense of the word.
(See p. 315.)

bauxitic.[1] Soil investigators, on the other hand, regard alumina as equally important with the iron oxide: they put the emphasis on the low proportion of silica.

The words "laterite" and "lateritic" are thus used with several different meanings, and it may happen that a soil called lateritic by a soil investigator would not be so designated by a geologist or an engineer.

Laterites may undergo secondary changes, such as the resilication discussed below, which considerably affect their composition but still leave them conforming to some of the criteria set out above. These altered soils are called lateritic soils or red earths.

Formation of Laterites.

Climate.—The climatic conditions usually associated with the formation of laterites are abundant rainfall and high temperature. Some investigators[2] emphasise the importance of alternations of wet and dry seasons, but Scrivenor and Harrison do not, while so far as the formation of free alumina is concerned Scrivenor, de Jongh, and Blondel attach more importance to the mineral composition of the rock than to the climate.

The effect of rainfall is very well illustrated in Mauritius,[3] an island roughly conical in form in which the rainfall varies within a few miles from 25 to over 150 inches per annum. Its geology is simple, the rocks are mostly doleritic basalts of a volcanic upthrust with later basaltic intrusions. The soils overlying the old rocks show the following variations in passing from regions of low to regions of high rainfall :—

[1] *Cf.* "The Ayrshire Bauxitic Clay," G. V. Wilson, *Mem. Geol. Surv.*, 1922. Neither these clays nor the fossil laterites of Ireland gave rise to lateritic soils.

[2] See H. Harrassowitz in Blanck's *Handbuch der Bodenlehre*, 1930, **3**, 363.

[3] N. Craig and P. Halais, *Emp. J. Expt. Agric.*, 1934, **2**, 349; *Mauritius Dept. Agric.: Sugar Cane Res. Sta. Bull.* No. 4, 1934.

SiO_2/Al_2O_3 Molecular Ratio in Original Rock 5·8.	Low Rainfall.	High Rainfall.
SiO_2/Al_2O_3 molecular ratio in total soil	1·87	0·43
,, ,, ,, ,, clay fraction	1·68	0·37
Clay, per cent. in soil	73	45
Exchangeable bases in m. equiv./100 grm. soil	24	4
*p*H	6·8	5·6

The organic matter, the C/N ratio, and the percentage of sand were all greater under the high than under the low rainfall.

High temperatures have the important effect of accelerating the weathering process and so carrying it beyond the stage it has usually reached in colder climates, and also of hastening the decomposition of the humic acid.

Non-persistence of Humic Acid.—Mohr [1] showed that true laterites occur in Java only where humus oxidises so rapidly as to eliminate the possibility of solution of the sesquioxides by organic acid. When the vegetation cover is denser the humic acid persists longer and podzolisation takes place (pp. 273, 318).

Parent Material: (a) Basic Rocks.—J. B. Harrison (1935), who devoted many years to the study of lateritic soils in British Guiana, and Scrivenor both maintain that true lateritic weathering occurs only on basic and intermediate rocks, not on acid rocks like granite. Harrison studied in detail the laterites derived from dolerites in British Guiana. The changes by which they are produced consist of hydrolysis, hydration, and oxidation, but they are confined to a relatively narrow zone on top of the parent rock. The lime feldspars are changed into crystalline gibbsite, $Al_2O_3 . 3H_2O$, and the lime and silica are washed out. The ferro-magnesian minerals, chiefly pyroxenes, are converted into yellow, orange, or red hydrated iron oxides. No mica or kaolin is found. This material he called " primary laterite." The extent of the change is shown by the fall in SiO_2/R_2O_3 molecular ratio : in the rock this is about 6 while

[1] *De Grond van Java en Summatra,* 2nd ed., 1930. An English translation has been made by R. L. Pendleton (1933).

in the laterite it is less than 1. The SiO_2/H_2O ratio also falls from over 100 in the rock to less than 0·5 in the laterite.

Under conditions of free drainage and high rainfall (2500 mm. or more per annum) this layer gradually deepens and the soluble products are washed out, but little or no further change occurs. The iron and alumina components are slowly separated, and the soil takes on a slaggy appearance: its structure becomes vesicular or vermicular through loss of minerals from the rock during decomposition.[1]

(*b*) *Acidic Rocks.*—For granites and acidic rocks, muscovite, etc., decomposition differs in one highly important respect. The potash feldspar is converted into secondary kaolins, unlike the lime feldspar, which yielded gibbsite, so that the SiO_2/R_2O_3 ratio instead of being about 1 is nearly 2. The iron-bearing minerals, however, biotite and ferromagnesian compounds, decompose as before to give hydrated iron oxides, so that the soils have the same colour as the true laterites; also again there is little subsequent change under conditions of free drainage, so that the layer of decomposed rock may be deep. This is, in point of fact, the material to which Buchanan gave the name laterite, though soil workers now call it lateritic soil or red earth. A somewhat different process occurs on acid igneous rocks in Nigeria and Kenya (p. 319).

The Time Factor.—Polynov points out that laterisation requires ample time for its completion, so that it occurs on old undisturbed rocks, not on recent intrusions, sedimentary rocks, or river terraces. He attributes the absence of laterites on granites to the circumstance that these are recent intrusions on which the process has not yet had time to complete itself.[2] In Madagascar laterites are found on very old basalts but

[1] For details and description of the profile see F. Hardy and R. R. Follett Smith (*J. Agric. Sci.*, 1931, **21**, 739-761).

[2] Some investigators (*e.g.* Bauer), on the other hand, have claimed that acidic rocks can give rise to laterites, but their identifications may not always have been good.

not on those of later, *e.g.* quaternary age;[1] these younger soils are brown to black in colour; they are shallower but more fertile than the red soils ultimately formed.

The course of the weathering in Sierra Leone (rainfall 90 to 150 inches) has been studied by Martin and Doyne.[2] Their analyses of the parent rock, norite, and its lateritic weathered product are as follows :—

	SiO_2.	Al_2O_3.	Fe_2O_3.	CaO.	Loss on Ignition.	Molecular Ratio, SiO_2/Al_2O_3.
The laterite	17·9	26·0	39·7	trace	14·6	1·17
Intermediate products .	28·3	28·7	21·6	trace	20·9	1·66
Parent rock, norite .	44·3	26·9	19·2	8·6	0·2	2·8

In this instance the iron has accumulated: it lies in the crevices formed by removal of the basic minerals, and it cements the yellowish flaky material into the characteristic orange-red vesicular rock. In other laterites much of the iron in the parent rock disappears.

Examples of extreme laterisation occurring elsewhere are shown in the following figures :—

	Silica.	Alumina.	Ferric Oxide.	Molecular Ratio, SiO_2/Al_2O_3.
Sierra Leone norite .	7·3	41·5	23·2	0·30
India basalt . .	3·90	54·80	13·7	0·12
Seychelles diorite. .	3·88	49·89	20·1	0·13
Madagascar granite .	4·6	60·86	1·0	0·13

Norite and basalt usually contain about 50 per cent. of SiO_2, diorite about 55 per cent., and granite about 70 per cent.

The laterites are usually deep, very porous and non-plastic: therefore less liable to erosion[3] than soils of higher

[1] H. Erhart, *C.R.*, 1929, **188**, 1561.

[2] *J. Agric. Sci.*, 1930, **20**, 135.

[3] H. H. Bennett, *Rept. Ninth Annual Meeting of the Amer. Soil Surv. Assoc.*, 1929, Bull. 10, pp. 55-74.

SiO_2/Al_2O_3 ratio. They lack cohesion, and their water relationships are rather special.

The bases having been largely leached out, the soils lack potash and lime, and as they contain free aluminium and iron oxides they have considerable power of absorbing P_2O_5,[1] hence they are notably deficient in "available" potash and phosphate. They are acid: the *p*H generally lies between 4 and 6. They contain much combined water: 10 per cent. in the British Guiana samples; 25 per cent. in Sierra Leone. They need good treatment and manuring, particularly with organic or green manures, but they are easy to cultivate.

The Altered Laterites: Red Earths or Lateritic Soils.

The formation of true laterite necessitates free drainage. When drainage is impeded secondary kaolin is formed and the SiO_2/H_2O ratio is over 0·8. The process of kaolin formation is not clear: Harrison attributed it to resilication of the gibbsite, but Hardy has been unable to reproduce this reaction in the laboratory. The granites as already mentioned also give rise on weathering to much kaolin, and the resulting soil appears to be similar to these altered laterites.

Both groups of soils are called red earths or lateritic soils. Like the laterites they are deep, and may be as much as 50 feet in depth.

The iron in all cases appears as hydrated ferric oxide, so that the soils are yellow or red according to the degree of hydration, the yellow and orange colour being associated with high hydration (turgite, limonite) and the red or crimson colour (goethite, hæmatite) with low hydration, *e.g.* where dry periods alternate with wet ones. Redness is therefore no indication of the iron oxide content of the soil nor of the degree of laterisation.

When the ground water is near the surface an iron pan

[1] See Martin and Doyne, *J. Agric. Sci.*, 1930, **20**, 135-143; and Seki, *Proc. Third Pan Pacific Sci. Cong.*, 1926, pp. 1936, 1941.

can form. J. A. Prescott [1] has suggested that in Australia and many parts of the tropics the iron pans and gravels, which are sometimes taken as typical of laterite, may in fact be fossil survivors from the swamps of late tertiary times.

The *red earths* resemble the true laterites in that one of their most striking physical properties is their marked porosity. Water drains through them so quickly that they may be ploughed within a few hours of heavy rain, even though they be clay-like in other respects; *e.g.* in having high "sticky points." They are also very friable and show small residual shrinkage. All these properties are attributable to the lack of cohesiveness of the kaolin. They vary considerably in their power of base exchange and of phosphate absorption: both these may be associated with the iron oxide present. The fertility of these red earths varies according to the degree of leaching: in some regions they are fairly fertile, in others they are not.

Leached or Podzolised Lateritic Soils.—Where the vegetation cover is sufficient to allow humus to persist the ordinary soil forming processes go on and are thus superimposed on this process of laterisation. Mohr [2] in Java described podzolised laterites in which iron and aluminium hydroxides had been carried down from the surface leaving a quartzose grey top soil merging downwards into almost uniform red earth, and Senstius [3] showed that the podzolisation proceeds substantially as in temperate regions, but it does not go to completion (see p. 273).

Marbut has also described podzolised laterites in the Amazon valley.[4]

The ecological relations of these various soils so far as they occur in the West Indies have been summarised by Hardy.[5]

[1] *Soil Res.*, 1933, **3**, 133.

[2] *De Grond van Java en Sumatra*, Amsterdam, 1922.

[3] *Soil Res.*, 1930, **2**, 10, 56.

[4] *Proc. 2nd Int. Cong. Soil Sci.*, Moscow, 1932, **5**, 72.

[5] F. Hardy, *Emp. J. Expt. Agric.*, 1933, **1**, 103; *Trans. 3rd Int. Cong. Soil Sci.*, 1935, **2**, 150.

Other Tropical Soils.

It is by no means safe to assume that weathering which takes place in the tropics, where mean temperatures of 30° C. or more are quite common, must necessarily follow the same lines as weathering in cooler regions under mean temperatures of 15° C. or less. H. C. Doyne and W. A. Watson [1] have described a group of soils, called by them "Ilepa," which are formed on acid igneous rocks in Nigeria and yet do not appear to be identical with the lateritic soils described on p. 315. These soils also, like some other tropical soils, increase in acidity in going down the profile, which is contrary to what happens in temperate climates. A typical "Ilepa" profile gave the following results :—

	Surface Soil.	Concretion Horizons.			Mottled Clay ("Ilepa") and Decomposing Rock.			
Depth, inches	0·8	8–16	16–24	24–34	34–46	46–58	58–70	Below 70
*p*H . .	5·5	5·3	5·2	5·2	4·7	4·5	4·4	4·2
Exchangeable base saturation per cent.	52	50	50	46	36	26	21	19

A good deal clearly remains to be discovered about tropical soils.

Tropical and subtropical red soils thus include :—

(1) Laterites, the result of the primary change of basic rocks, the characteristic of which is the presence of free alumina, probably gibbsite, and the absence of secondary kaolinite.

(2) Lateritic red soils formed on acidic rocks or resulting from subsequent and secondary changes in laterites. These are characterised by the presence of much secondary kaolinite and absence of free alumina in any quantity.

(3) The leached or podzolised laterites or lateritic soils: here, however, the surface layer may be grey.

[1] *J. Agric. Sci.*, 1933, **23**, 208 ; H. C. Doyne, *ibid.*, 1935, **25**, 192 (data from p. 196).

(4) Terra rossa, derived from limestones.

(5) Other red or yellow soils formed under other conditions, *e.g.* the red soils of Madagascar formed on clay marls.[1]

Principles of Soil Management.

In the management of soil two general methods of treatment are adopted :—

(1) A scheme of husbandry is adopted which accords as closely as possible with the conditions, and the small necessary adjustments are made by methods discussed later.

(2) The soil is converted into one of the calcium type to which cultivators are normally accustomed and for which their varieties of crops, implements, and systems of management were evolved.

Usually the first of these is adopted if the soil is far removed from normal conditions, and the second where the necessary changes are not too great.

Management of Podzolised Soils.

The reclamation of a podzolised soil necessitates three processes :—

(1) The neutralising of the acidity.

(2) The conversion of the acid humus and acid clay into calcium combinations.

(3) The bringing up to the surface of the humus and other constituents that have been washed down.

The first and second require the same treatment, and are in the main the same thing. Lime, limestone, or chalk are added in amounts estimated as already indicated (p. 214).

D. L. Askinazy and S. S. Yarusov [2] show that the lime stimulates decomposition of the humus, enriching the soil solution in inorganic nitrogen and phosphates, and raising both yield and percentages of nitrogen and P_2O_5 in the crop during the first year. The improvement in nitrogen supply

[1] H. Erhart, *C.R.*, 1929, **188**, 1561.

[2] *Trans. Sci. Inst. Fert.*, Moscow, No. 57, 1928.

became less as time went on and ceased entirely in the ninth year; the improvement in phosphate supply, however, continued.

The bringing back of some of the material washed down from the surface soil is achieved by deep ploughing.

Excellent examples of reclamation can be seen in Jutland, where the heaths are being converted into farms and forests by methods worked out by Fr. Weis and his assistants. The heaths are typical podzols with a layer of raw humus on top underlain by grey bleached sand very poor in humus; below this is the black humus hard pan, the humus of which contains about 3 per cent. of nitrogen; below this the mottled greyish-brown iron pan and then the deep yellow-brown sand. The first step is to burn the heather, the hard stems of which would greatly impede future work; this is followed in autumn by a shallow ploughing (15 cm.) to turn over the raw humus, then by disc harrowing in the following spring. In the next autumn the soil is ploughed deeply to bring up both humus and iron pans. Marl (50-60 per cent. $CaCO_3$) is then applied at the rate of 12-15 tons per acre.

In the following spring these various constituents can be mixed by cultivators and harrows, and a mixture of oats and summer rye is sown as preliminary to a suitable mixture of grass and clover. The land is now capable of carrying agricultural crops, appropriate rotations of which have been designed.

For forestry purposes it is not necessary to carry the reclamation so far. Suitable trees are *Picea excelsa* and *Pinus Montana*, which go well together,[1] but others are being investigated.[2]

[1] P. E. Müller thought that *P. Montana* helped in the nitrogen nutrition of the *Picea* by increasing nitrogen fixation. This view is now given up: more probably it shades the soil, so preventing the growth of heather and other plants which assimilate nitrate and produce raw humus, and check the accumulation of nitrate in the soil.

[2] Fr. Weis, *Det. Kgl. Danske Videns. Selskab. Biol. Medd.*, No. 9, 1929, **7**, 1-196; No. 3, 1932, **10**, 1-202; *Proc. Int. Soc. Soil Sci.*, 1929, **4**, 254.

An interesting example of reclamation of a podzol in New Zealand is furnished by the treatment of the Pakihi lands of the Nelson Province,[1] a considerable area of land having all the characters of a humus podzol. Burning of the wild vegetation, followed by liberal treatment with lime (2 tons per acre) and basic slag (5 cwt. per acre), then thorough disc cultivation, was sufficient treatment preliminary to sowing with mixtures of seeds and grasses: no deep ploughing or breaking of the hard layer was necessary.

Management of Irrigated Soils.

The essential features in the management of irrigated land are:—

(1) The exclusion of soluble salts.

(2) The removal of excess of water from the soil and the keeping down of the level of the subsoil water.

I. *Salt and Water Problems.*

Sodium salts may be brought into irrigated land in two ways:—

(1) In the water used for irrigation.

(2) By seepage from higher land.

The likelihood of injury depends on the texture of the soil and on the drainage: a light sandy well-drained soil is most tolerant of salt, and a heavy badly-drained soil is least tolerant.

Some of the salt contents of irrigation waters are given in Table 62.

The movements of water in the soil must be controlled as rigidly as is possible. The soil frequently contains soluble salts which dissolve in the water and may then be carried to lower ground where they accumulate, kill the vegetation, and finally sterilise the land. Many instances of damage due to

[1] T. H. Easterfield, T. Rigg, and J. A. Bruce, *N.Z. J. Sci. Tech.*, 1929, 11, 231.

TABLE 62.—TOTAL DISSOLVED SOLIDS IN WATER USED FOR IRRIGATION.

	Parts per Million.	
	Suitable.	Unsuitable.
White Nile	150	—
Blue Nile	120	—
Murray River (Australia)	96·5	—
Bombay (Nira Valley) good water	470	—
" " " bad "	—	1350-3600
Oudh Canal	212	—
" Well	—	1000
Arkansas (Rocky Ford)	—	2000
Jordan River (Utah)	890	—

seepage could be quoted. In general the distribution of the salt is uneven; certain patches may contain much more than the rest of the ground. These should be located by means of a soil survey,[1] and carefully kept out from the irrigation system; the difficulties due to the salt are thus minimised. The process is less wasteful than it appears, for in most irrigation systems there is more land than can possibly be watered. All practicable steps must be taken to avoid leakage of water from the channels: cement linings are rarely practicable and less costly devices are used, such as a drainage ditch on the lower side of the canal to intercept the water soaking away. Drainage water from the irrigated land should not be allowed to wander where it will, but be led to some definite place where it can do no harm to the main area.

When land is irrigated no more water than is absolutely necessary for the plant should be used, for all harmful effects of the salts carried on to the land by the irrigation water are cumulative (p. 575).

Irrigation may also raise the ground-water level, and since the ground water in general contains large quantities of salt this raising may spoil a great deal of land, in any case it may asphyxiate the roots. Fig. 37 shows the falling yield of

[1] For examples of suitable surveys see *Imp. Bur. Soil Sci. Tech. Comm.* No. 15, 1930, South Africa.

cotton on land in Egypt since it was brought under intensive irrigation.

Saline soils that have been formed from normal soils by the intrusion of salts from ground water are called " regraded " alkali soils by the Russian workers. Vilensky (1930) gives details of their morphology. In general, the calcium carbonate horizon is undisturbed but the sulphates and chlorides move upwards. Calcium chloride is the first salt to appear

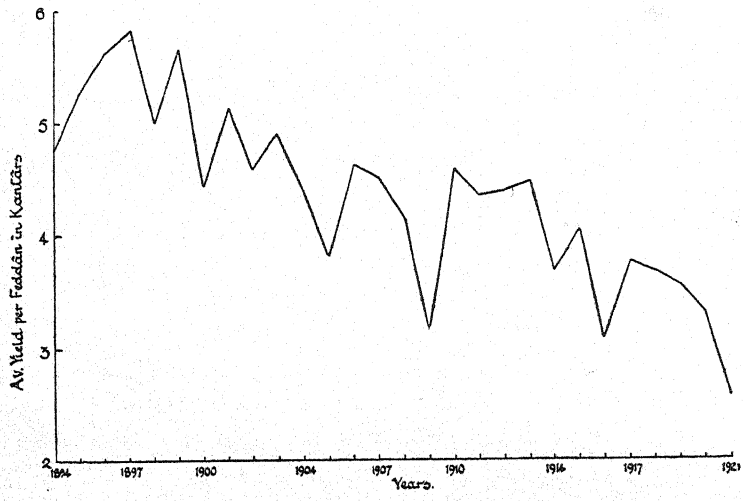


FIG. 37.—Yield of cotton, kantars per feddan, in Egypt in successive years after intensive irrigation began. (1 kantar = about ·100 lb. lint; 1 feddan = 1·038 acres.) (E. McKenzie Taylor and A. C. Burns.[1])

on the surface; sodium chloride and sodium sulphate come later. When the soil is being drained, however, calcium sulphate is the last salt to disappear from the surface. Thus in a regraded alkali soil gypsum occurs above the calcium carbonate horizon, not below it as in a solonetz. The reclamation of these soils can only be accomplished by a lowering of the ground-water level which may be exceedingly difficult.

[1] *Egypt. Min. Agric. Tech. Bull.* No. 25, 1922.

II. *The Formation of Sodium Carbonate ("Black Alkali") in Soils.*

Where a sodium clay exists naturally, or has been formed through the introduction of sodium salts, its hydrolysis leads to conditions very inimical to plant growth; the alkalinity, the stickiness, the pan with its accompaniment of water logging are all harmful. The sodium hydroxide and carbonate simultaneously formed show their presence easily because they dissolve some of the humus, forming a black solution which collects in little puddles and on evaporation leaves a black deposit. The farmers of the Western States therefore long ago gave it the name of "black alkali," and, rightly associating it with the bad conditions, attributed them to it. It had also been recognised in Egypt and in Russia, and much work had been done to trace its origin.

These investigations played so important a part in the development of modern soil science that an account of them must be given.

The work was begun by the French chemists, the problem being brought to their notice when Napoleon, in the closing years of the eighteenth century, brought Egypt under French domination. Berthollet supposed that the sodium carbonate was formed by the interaction of sodium chloride and calcium carbonate.[1] This hypothesis was generally adopted in Europe, and supported by Hilgard's school in California and by the physical chemists in the United States Bureau of Soils.[2]

[1] C. Berthollet, "Observations sur le Natron," *J. de Physique de Chimie et d'Hist. Nat.*, 1800, **51**, 1-9. An interesting study of the "Vallée des lacs de natron" in Egypt.

[2] Hilgard and Weber, *Amer. Soc. Promotion Agric. Sci.*, 1888; Hilgard, *Calif. Expt. Sta. Rept.*, 1891, p. 87; Jaffa, *ibid.*, 100; F. K. Cameron, *U.S. D.A. Bur. Soils*, Bulls. Nos. 17 and 18, 1901; W. P. Kelley, "The Effect of Nitrate of Soda on Soils, *Calif. Expt. Sta. Rept.*, 1916, p. 59; J. F. Breazeale, "Formation of Black Alkali (Sodium Carbonate) in Calcareous Soils," *J. Agric. Res.*, 1917, **10**, 541.

As alternatives Cameron[1] and Hall and Miller (1905) introduced two different biological explanations, both supposing that the carbonate may be formed by the growing plant, but Cameron assumed an excess absorption of alkali bases over acid by the plant, which excess, on decay, would remain in the soil as alkali carbonate, while Hall made the reverse assumption, supposing an excess absorption of acid (*e.g.* the nitrate ion) over base, leaving alkali carbonate in the soil.

These hypotheses proved insufficient. The explanation now accepted was first put forward as the result of an ingenious investigation by Paul de Mondésir in 1888.

Finding calcium chloride in the water extract of a soil near the sea, he argued that it must have been formed by sodium chloride. But where had the sodium gone? There was too much to have been taken by the crop, and he concluded it must have been absorbed by the soil. Direct laboratory experiments showed that soil reacted with sodium chloride to give calcium chloride and an insoluble sodium compound. After removal of the calcium chloride this sodium compound readily broke down in presence of CO_2 to give sodium carbonate, and by successive treatments of a soil first with sodium chloride, then with water, and finally with CO_2 and water, he was able to prepare 100 grms. of sodium carbonate from 1 kilo of soil. His explanation, therefore, was that sodium chloride does not react with calcium carbonate, but with soil, forming a sodium absorption complex which, after removal of the calcium chloride, can be decomposed by CO_2 or calcium carbonate.

This paper was, unfortunately, overlooked, and the American workers continued to base their investigations on the old Berthollet hypothesis. Thirty-four years later the

[1] Cameron was led to this investigation by a belief, popular in the Western States of America, that certain plants, notably the common Greasewood (*Sarcobatus vermiculatus*), converted harmless salts into sodium carbonate in the soil.

same explanation was put forward by Gedroiz (1912), who, as he does not mention Mondésir's work, was apparently unacquainted with it. By a curious fatality, Gedroiz's work, in turn, passed unnoticed for twelve years, until it was translated from the Russian by the United States Department of Agriculture, and so made available for scientific workers.

In studying the alkali soils of Russia, Gedroiz had observed that the quantities of sodium carbonate extracted by water diminished in successive extractions, but less than if the sodium carbonate existed as such in the soil. He concluded, therefore, that the sodium carbonate is either held by absorption, or that it is continuously being produced in the soil.

He next showed that the amount of sodium carbonate washed out was lowered on adding sodium chloride or sulphate but increased after these salts were removed. This result does not allow of discrimination between the two possibilities, but it amplifies them; if the sodium carbonate is held by absorption, this is intensified by sodium chloride and sodium sulphate; alternatively, if it is being formed in the soil it cannot be directly from sodium chloride or sodium sulphate, as supposed in the old view.

He then added sodium chloride and calcium carbonate to soil and extracted with water; but he obtained only little sodium carbonate. Finally, he added sodium chloride alone, extracted with water, and then added calcium carbonate and again extracted, and obtained a great deal of sodium carbonate, much more than when no sodium chloride had been added.[1]

It appeared, then, that the formation of sodium carbonate proceeds in three stages: the first is the reaction between sodium chloride and the soil; the second is the leaching away of the soluble products; and the third is the reaction between the insoluble sodium product and a carbonate.

[1] A. B. Cummins and W. P. Kelley (*Univ. Cal. Agric. Expt. Sta. Tech. Paper* No. 3, 1923) independently used this method to convert an acid soil first into a neutral and then into an alkaline one, and thus they demonstrated the simple relationship between acidity and alkalinity in soil.

The simplest explanation was to suppose that the sodium chloride reacted on the " zeolitic silicates " to form a sodium clay which then reacted with the carbonate to form sodium carbonate and a calcium clay. The paralysing influence of sodium chloride and of sodium sulphate follows, naturally, as these salts interfere with the exchange between calcium carbonate and the sodium in the clay.

This explanation of the origin of sodium carbonate gave the clue to the treatment of " black alkali." Simple washing away of the carbonate with water, formerly advocated as a remedy, is obviously insufficient so long as the clay remains a sodium clay; replacement of the sodium by calcium is a first necessity for a permanent cure; the next step is to prevent the reformation of the sodium clay.

Hilgard used calcium sulphate (gypsum or land plaster) with success in some instances where he was able to arrange for proper flooding and draining of the land, but in estimating the amount required he took into account only the sodium carbonate washed out from the soil by water.

III. *Conversion of Sodium into Calcium Soils: Reclamation of Alkali Soils.*

There are three stages in the reclamation or conversion of a sodium into a calcium soil :—

(1) The replacement of sodium in the absorption complex by calcium.

(2) The removal of the sodium salt formed during this replacement and the exclusion of all new supplies of sodium.

(3) The neutralisation of the alkalinity;

(3) would naturally follow when (1) and (2) are complete, but it can be facilitated in other ways, and this expedites the whole process.

The conversion of sodium into calcium soils can be effected by treating the sodium soil with calcium sulphate when a double decomposition takes place, forming calcium clay and

sodium sulphate which can be washed out. Where the drainage is good, and a sufficient supply of gypsum is available, the process is satisfactory; it is, however, imperative that no new

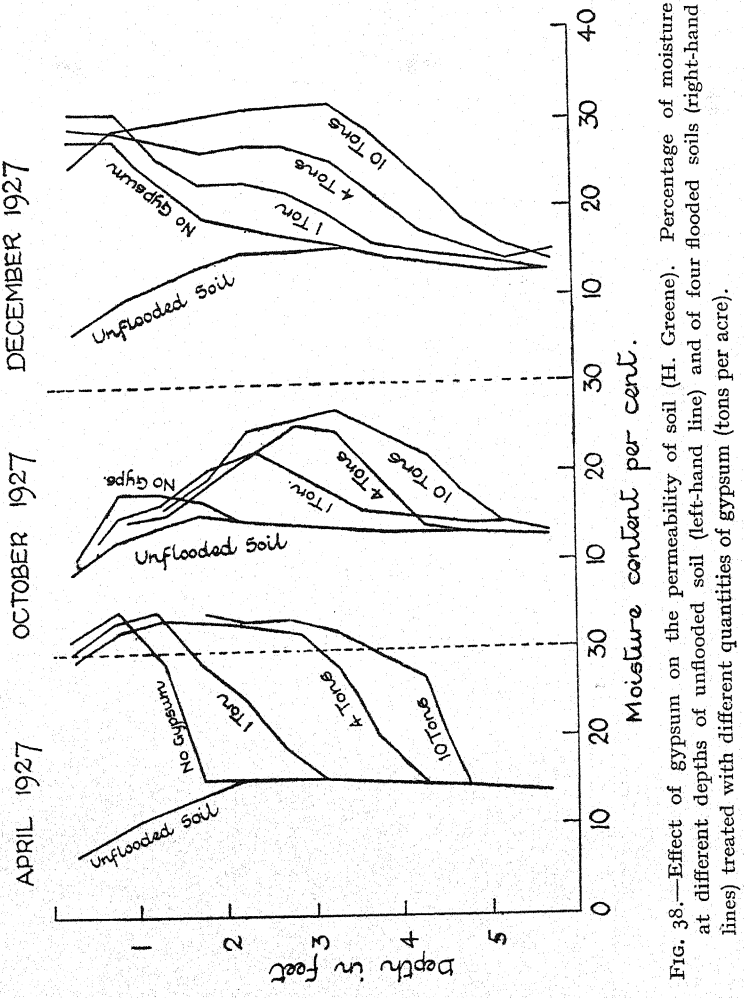


FIG. 38.—Effect of gypsum on the permeability of soil (H. Greene). Percentage of moisture at different depths of unflooded soil (left-hand line) and of four flooded soils (right-hand lines) treated with different quantities of gypsum (tons per acre).

sodium should be brought in. The benefit tends to be cumulative because the gypsum increases the permeability of the soil and so facilitates the removal of the sodium. This is well

shown in H. Greene's experiments in the Gezira [1] (Fig. 38). The soil here is a heavy sodium clay, and very impermeable. It was flooded in April, then after an interval the percentage of moisture at different depths was determined. No more water was applied and a second set of determinations was made in October. In December the land was again flooded and the distribution of the water again determined. Without gypsum the water remained near the surface: with increasing dressings of gypsum it penetrated deeper and deeper into the soil. The drying out affected the first two feet equally whatever the gypsum treatment, but it did not equally affect the lower depths: the stores of water let down by the heavier dressings remained.

Green manuring brings about considerable improvement. Deep rooting crops, such as *Melilotus alba*, lucerne, etc., are grown; they tolerate and absorb a certain amount of salt, and force a way through the compact layer, leaving when they die a network of channels along which water can percolate instead of lying on the surface. When they, or any residues left after taking a hay crop, are ploughed in, they add humus to the soil which masks the harmful effects of soluble salts.

Once improvement is effected and cultivation becomes possible three rules must be strictly observed:—

(1) Water must be used in the smallest possible quantities: the systems of irrigation must reduce waste to a minimum.

(2) Efficient drainage must be provided.

(3) Salt tolerant crops and varieties should be grown: rice, and in Egypt, dineba (*Panicum crus galli*) are very useful.

The Artificial Acidifying of the Soil.

In certain conditions it is necessary to push the reaction of the soil in the direction of greater acidity; *e.g.* in reclaiming alkali land and in making soil conditions less favourable to the growth of certain undesirable plants or organisms (p. 543).

[1] *J. Agric. Sci.*, 1928, **18**, 531.

Three methods are adopted in practice :—

(1) Powdered sulphur is added to the soil at the rate of about 20-30 cwt. per acre. It becomes oxidised under the influence of certain soil bacteria to form sulphuric acid (p. 402).

The sulphur may, however, retard nitrification if it makes the soil too acid, and in that event it does not increase the growth of crops [1] as much as might have been expected.

(2) Ferrous or aluminium sulphate is added. Hydrolysis occurs and free sulphuric acid is liberated.

(3) Ammonium sulphate is added. This interacts with the calcium carbonate in the soil forming calcium sulphate which washes out. The loss of calcium tends gradually to make the soil acid (p. 230).

(4) Green manures are ploughed in.

IV. *Reclamation of Alkali Soils in the United States.*

The problem of alkali was one of the troubles of the early agricultural settlers in the Western States, and it was studied in detail by Hilgard, the founder of the Californian School of soil investigations. His results are embodied in a series of reports and were summarised by him in his book on Soils (1906); he emphasised the value of gypsum treatment and flooding, and opened up lines of investigation which have been ably developed by his successors.

Methods of reclamation have been studied by Kelley and his colleagues at Fresno, in the San Joaquin Valley, California. The valley is wide and level, and is here about 300 feet above sea-level. The soil is a light sandy loam containing calcium carbonate in small but variable amounts, underlain by a calcareous hard pan which, however, is permeable to water. Originally it was cultivated continuously for wheat, then for barley, then with closer settlement for fruit: this last development necessitated the breaking of the pan (often by explosives) and irrigation, which was done without large scale drainage. From 1890 to 1900 the Fresno land was a fruitful

[1] *Rept. of Govt. Chemist*, Khartoum, 1928.

vineyard; the water table was 80 feet below the surface. Then as irrigation schemes developed the water table rose—a very usual occurrence; salt was brought up in patches, first turning the leaves brown, then killing the plants.

The bare land is as usual spotty in appearance: there are black patches where the soil dries hard as a rock and peels in flakes; other patches glistening with particles of sand; others where weeds—especially *Atriplex bractiosa* and *Tissa salina*—grow, and yet others where certain tolerant crops, such as *Melilotus alba*, are possible. Rain puddles the soil so badly that the water lies on the surface and will not soak in, except where Melilotus has grown.[1]

W. P. Kelley[2] began his reclamation experiments in 1919: his general method was to reverse the process of formation, to lower the water table, then to remove the salt, and finally restore the calcium in the absorbing complex.

This was accomplished slowly by irrigating the land by water raised from wells, and more rapidly by supplementary treatments.

Addition of gypsum with subsequent flooding was effective. Twelve tons per acre, however, was needed for the full effect: this brought down the *p*H value from 10 to 7·3. Smaller quantities were less effective. The best results were obtained by using sulphur at the rate of 3600 lb. per acre. At first this made little change, but after about three years it caused a striking improvement, shown by good growth of lucerne. It was converted into sulphuric acid (p. 402) which had two effects: it neutralised sodium carbonate, and it brought calcium into solution as calcium sulphate which then proceeded to exert the gypsum effect. Within seven years all the sodium carbonate and some of the calcium carbonate was removed from the top two feet of soil. The best way of using the sulphur was to leave it to act without watering

[1] The soil does not show the columnar solonetz structure, and it rather resembles the solonchak.

[2] *J. Agric. Sci.*, 1934, **24**, 72.

for two years, cultivating the soil just sufficiently to maintain a mulch; during this time oxidation to sulphuric acid and interaction with the carbonates were both completed: then a good quantity of water was given to remove the sodium sulphate: finally *Melilotus alba* was grown and ploughed in as a green crop. The ground was then ready for cropping and lucerne could be grown successfully. This builds up soil organic matter and breaks the calcareous pan so opening the way to fruit production.

V. *Reclamation of the Hungarian Alkali Soils: "Szik" Soils.*

Alkali soils occur in Europe, notably in Russia and in Hungary. The Russian investigations have already been described (p. 297). The Hungarian investigations are less well known than they deserve because of the language difficulty: they have, however, recently been summarised by de 'Sigmond,[1] one of the leaders in this subject. The soils are known as "szik" soils, and fall into two main types, the soda szik, corresponding to the solonchak, containing soluble salts, and varying from a light sand to a medium clay surface soil, rich in calcium carbonate but underlain by a very impermeable layer; and the heavy clay szik, much like a heavy solonetz clay soil, containing replaceable sodium in the absorption complex, but usually no soluble salts or calcium carbonate. The soda szik soils are reclaimed by washing out the salts, for which purpose appropriate methods have been designed. The heavy clays are reclaimed by:—

(*a*) Checking the upward movement of salts: this is done by reducing evaporation of surface cultivations, and also by growing lucerne which dries out the soil and so stops salt movement.

(*b*) Rendering the pan pervious by the use of calcium carbonate, press lime from sugar factories, gypsum, and

[1] "Hungarian Alkali Soils and Methods of their Reclamation," *Univ. Calif. Agric. Expt. Sta.*, special publication, 1927; *Imp. Bur. Soil Sci. Tech. Comm.* No. 23, 1932.

farmyard manure which generates CO_2 and so helps to bring the calcium carbonate into solution.

(*c*) On one type of soil by bringing up marl from the subsoil and spreading it on the surface.

VI. *Reclamation of Soils Damaged by Sea Water.*

Some interesting observations on the formation of a sodium clay by flooding with sea water were made by T. S. Dymond in 1897-1899.[1] The first effect of the flooding was to kill the vegetation by direct action of the salt. But when the flood subsided and the rain water began to wash away the salt, an interesting sequence of events was observed. The soil was at first "in remarkably good condition, ploughing well and forming a capital seed bed." But with further removal of the salt "this condition gradually altered until the soil became difficult to work and in dry weather hard and cindery." The clay became more deflocculated, and would remain suspended for weeks in water while that from the unflooded land settled in a few hours.[2]

Dymond proved that the effect of the salt was to displace calcium and magnesium from the clay, and he argued that sodium had taken their place. He attributed the initial favourable physical conditions to the flocculation brought about by the small quantity of salt still left; when this was gone the clay became highly deflocculated.

The general outlines still hold good, though later work

[1] T. S. Dymond and F. Hughes, *Report on Injury to Agricultural Land on the Coast of Essex by the Inundation of Sea Water on 29th Nov., 1897*; Chelmsford, 1899.

[2] An interesting example occurred later at E. Halton in North Lincs. The land was formerly very productive, being especially suited for wheat and beans; it was flooded by the sea in 1921 and became infertile. It has not since been flooded, but it remains very sticky when wet and hard as concrete when dry, so that cultivation is impossible; even wild plants make but little growth (H. J. Page and W. Williams, *J. Agric. Sci.*, 1926, **16**, 551-573). In 1931 it still showed signs of deterioration, but the wild white clover sown in the grass mixtures had done well. It appeared, however, that the under drains were choked with deflocculated particles.

has shown that sea water puts more magnesium than sodium into the clay.[1]

Dymond's observations are in full accordance with Dutch experience around the Zuyder Zee. The flooded soils of "Kweldergronden" remain open and porous so long as they are exposed to occasional floods, but after they are protected by dykes, they lose their salt through the action of the rain, and gradually become sticky and impervious to air and water when wet, and very hard when dry.[2]

Recently, the Dutch have begun a large reclamation scheme in the Zuyder Zee, and an intensive study of the reclamation of land previously covered by the sea. The scheme consists in—

(*a*) Damming the Zuyder Zee across its mouth.
(*b*) From the lake so formed, recovering four large areas of land called polders.

The central and deep part of the lake is to remain under water, and will form the Yssel lake, 270,000 acres in extent, its surface being 16 inches below the normal Amsterdam sea-level. This will receive the waters of the Yssel river and its water will become fresh, instead of being salt, as at present.

The freshening of the water of the Yssel lake will have great value in North Holland, where under present conditions water becomes so scarce in times of drought that the water supply to the cattle must be considerably curtailed. After the reclamation a system of irrigation and watering of this northern region will be set up.

At Andijk there is an experimental polder of 110 acres on which different methods of cultivation and of removing salt from the soil are being tried. There is still some salt in the ground, but not enough to interfere with cultivation: the

[1] Kelley and Liebig, *Bull. Amer. Soc. Petrol. Geol.*, 1934, **18**, 358; M. L. M. Salgado, *J. Agric. Sci.*, 1933, **23**, 18.

[2] For an account of these soils see Hissink's report in *Verslagen Rijks. Proefstations*, No. 29, 170-184, 1923.

most successful crops are barley, sugar beet, rape, mangolds, and potatoes: peas and beans were not so good.[1]

The improvement of the soil has been studied in detail by D. J. Hissink, whose reports[2] provide some of the most important information yet obtained on the reclamation of land from the sea. Hissink shows that the soil first left after the water has drained away is infertile because it contains a sodium clay; the essential operation in the reclamation, therefore, is to change this into a calcium clay. Happily the soil contains so much calcium that nothing more is needed except (1) adequate drainage so that the sodium chloride can wash out from the soil, and (2) cultivation and cropping of the soil so as to produce carbonic acid, which brings the calcium into solution and enables it to interact with the soil complex forming the calcium clay. The process takes time: it proceeds from the top downwards, but as soon as a seed-bed depth is in good condition cropping can begin and the presence of the unchanged sodium clay in the subsoil is little or no disadvantage.

Some interesting observations have been made on the properties of the sodium clay. In its raw condition it is sticky and infertile and exceedingly wet; it may contain up to 200 grm. of water per 100 grm. of dry soil, and the excess of salt is harmful to vegetation. By the second year it has dried considerably and much of the salt has been washed out by the rain, but sufficient remains to flocculate the clay so that it loses its stickiness; indeed its texture may be better than in normal soils: if this condition could be maintained some system of agriculture could be successfully practised. But the washing out of the salt by the rain continues, and in the third year so much has gone that the clay is no longer

[1] *De afsluiting en gedeeltelijke droogmaking van de Zuiderzee*, The Hague, 1930.

[2] *Rapporten met betrekking tot de bodemgesteldheid van de Wieringermeer en van den Andijker Proefpolder*, 1929, No. 1, pp. 81-288; *Brit. Ass. Repts.*, 1931, p. 512, and several papers in *Trans. 6th Comm. Int. Soc. Soil Sci.*, Groningen, 1932, A, and 1933, B.

flocculated but becomes again sticky and difficult to work. By the fourth year the calcium has begun to act and a normal calcium clay is formed, which the Dutch farmers understand, and for which their crops and cultivations are suitable. Agriculture can therefore start in full earnest.

Table 63, taken from Hissink, shows how the proportion of divalent to monovalent exchangeable bases in some of these soils affects their physical condition in the absence of salts.

TABLE 63.—INFLUENCE OF THE PROPORTION OF DIVALENT TO MONOVALENT BASES ON THE PHYSICAL CONDITION OF SOME DUTCH SOILS.

Physical State.	100 Parts of Replaceable Bases Contain:					
	Ca.	Mg.	Sum of Bivalent.	K.	Na.	Sum of Univalent.
Good, normal clay	79·0	13·0	92·0	2·0	6·0	8·0
Fairly good .	65·8	17·6	83·4	4·0	12·6	16·6
Bad . . .	42·1	25·0	67·1	6·5	26·4	32·9

Drainage is done in the first instance by letting the soil dry out: then either tile drains are laid or ditches are dug. Cultivation is commonly shallow, for deep cultivation would bring up wet soil containing much sodium clay or sodium salts. The crops grown are barley, sugar beet, mangolds, rape, and potatoes, and rotations do not seem to influence the yield. The soils are fertile, no artificial fertilisers yet appearing to be necessary.

Pan Formation.

The name "pan" is given to the hard compact layer formed during podzolisation or solonisation below the surface at depths of 25 cm. or more. Two kinds of pan have already been mentioned on pages 275 and 300.

(1) Iron and humus pans, formed by precipitation of the humus and ferric oxide sols, together with clay and alumina in the lower depths of acid soils.

(2) Pans formed from sodium soils under arid, alkaline conditions. As the result of local flooding where the parent material is poor in iron the pan is white, otherwise it may be red and be classed as an iron pan.

Two other kinds have been described :—

(3) Silicic acid pans, which, however, are by no means common.

(4) Calcareous pans which occur in arid conditions.

Pans are of great technical importance because they impede free root development and so cut the plants off from the reserves of subsoil water ; also they hold up temporary excess of water and prevent it soaking away. Thus plants are liable to suffer alternate extremes of drought and of water logging, always a bad thing for their growth.

No chemical method is known for getting rid of pans. They are broken mechanically by deep cultivation and by growing deep rooting plants such as lucerne, or when they are very hard they may be shattered by explosives, special types of which have been designed for this purpose.[1] Acid soils must, however, be neutralised with lime or the pan begins to form once more.

Effect of Drying and Heating Soils.

When a soil is dried or warmed, particularly when it is dried and warmed at the same time, as in summer, various changes occur which cannot yet be satisfactorily explained, nor is the relative importance of temperature and of drying yet known.

(1) The solubility of the phosphoric acid, inorganic electrolytes and organic matter is increased both on drying the soil

[1] See R. S. Smith, *Ill. Agric. Expt. Sta. Bull.* No. 258, 1925 ; C. W. Burrows, *Agric. Gaz. N.S.W.*, 1919, **30**, 153-167, 381-390 ; P. H. Haviland, *Rhod. Agric. J.*, 1928, **25**, 435-450 ; E. R. Gross, *N.J. Expt. Sta.*, Circ. 159, 1923 ; G. R. Boyd, *Proc. 1st Int. Cong. Soil Sci.*, Washington, 1928, 4, 765-770 ; A. Bruttini, *Agricoltura Ital.*, No. 4, 1919, pp. 21-31. See also p. 548.

at room temperature [1] and on heating a damp soil.[2] This change is reversed if the soil is left cool and damp for sufficiently long: the solubility of the phosphoric acid and inorganic salts falls to the level of the undried soil; that of the organic matter, however, always remains somewhat higher.

(2) The nitrate content tends to decrease on drying or heating but the ammonia content increases.[3]

The magnitude of these effects depends on the soil type; in the Russian work it was larger for chernozems than for podzols.

(3) The clay properties of the soil become less pronounced; the clay particles cement themselves together and act as silt or fine sand particles. Thus the soil of the Gezira (Sudan) is a very heavy clay which could not be cultivated in England, yet in this hot dry climate it readily crumbles as if it were a loam so long as no water is added.

(4) The quantities of exchangeable bases and of exchangeable hydrogen in a soil seem to change with changing temperature or dryness; this was shown by Vinokurov [4] for field soils under different cultivations throughout two years, and by J. L. Steenkamp [5] at Oxford, for soils dried at the ordinary laboratory temperature. H. G. Coles and Morison [6] showed that the acidity of all mineral soils increased considerably on prolonged heating at 98°, followed by a slight decrease on further heating. The changes were reversible. Peats showed slow changes, but not until all the water had been removed, and the changes were irreversible.

As shown on page 214, the change of acidity on drying

[1] J. L. Steenkamp, *Soil Sci.*, 1928, **25**, 163-182, 239-251, 327-332.

[2] A. Achromeiko, *Ztschr. Pflanz. Düng.*, 1928, A, **11**, 65-89.

[3] A. N. Lebediantzev, *Soil Sci.*, 1924, **18**, 419.

[4] *Pedology*, No. 3-4, 1928, **23**, 46-93. F. Terlikowski, S. Sozański and M. Kwinichidze (*Rocz. Nauk Roln.*, Poznań, 1936, **37**, 34) found that the mobility of potassium was increased but that of calcium decreased by drying the soil.

[5] *Soil Sci.*, 1928, **25**, 163-182, 239-251, 327-332.

[6] *Ibid.*, 1930, **29**, 59.

a soil in air at ordinary laboratory temperature is only small.

Drying or heating a soil thus increases its productivity: and long storage of a dry soil gives still further increases. Gedroiz's [1] experiments with oats grown in soils kept for a number of years are given in Table 64.

TABLE 64.—EFFECT OF STORAGE IN A DRY STATE ON THE PRODUCTIVENESS OF SOILS. OATS, GRAMS PER POT. GEDROIZ.

Number of Years of Storage.	No Manure.	Complete Manure.	Without Nitrogen.	Without Phosphate.
0	10·3	83·5	13·5	11
1	17·8	83·9	32·0	19
3	24·6	90·9	23·6	35·4
5	25·0	102·8	32·2	42

The effect is not entirely physical, since important biological changes follow the resulting partial sterilisation. Prescott has taken account of these changes in his studies of the drying of Egyptian soils,[2] as also has Lebediantzev [3] in studying Russian soils (see p. 478).

[1] *Bull. Bur. Agric. Int. Inst. Agric.*, Rome, 1915, **6**, 37. For other results see A. F. Gustafson, *Soil Sci.*, 1922, **13**, 173-213.

[2] The remarkable effect of drying (*sheraqi*) is described by Prescott in *J. Agric. Sci.*, 1919, **9**, 216-236, and 1920, **10**, 177; and by V. Mosséri in *Int. Rev. Agric.*, Rome, 1926 (n.s.), **4**, 1.

[3] *Soil Sci.*, 1924, **18**, 419-447, also *J. Landw. Wiss.*, 1926, **3**, 243-258.

CHAPTER V.

THE SOIL IN NATURE: II. THE CHANGES IN THE ORGANIC MATTER.

THE organic matter of the soil comes originally from the organic compounds built up by the plant from the carbon dioxide of the air; some of it, however, has been modified by micro-organisms and other agencies in the soil. It is essentially a transient constituent; new supplies are continuously being added, and the older material is continuously being decomposed, but in any given soil the various processes settle down to some kind of equilibrium so that the organic matter remains fairly constant both in amount and in composition, so long as the general conditions remain the same. But it is a mobile equilibrium, and changes are continuously going on, which, however, tend to balance one another.

We shall deal first with the accumulation of organic matter and then with the decomposition.

The Accumulation of Soil Organic Matter.

The accumulated organic matter represents the difference in activity of plants in making fresh supplies and of micro-organisms in decomposing them. High temperature favours decomposition, and restricted air supply favours accumulation. In hot, dry, or well-drained conditions the destructive action predominate: ants and other insects and micro-organisms are active, and humus has no chance to accumulate. Well-aerated soils exposed to an average temperature of 25° C. and more, such as those of Java [1] and of the Gezira (pp. 339, 408), contain very little humus or nitrogen.

[1] E. C. J. Mohr, *De Grond van Java en Sumatra*, 2nd ed., 1930.

In North America, Jenny [1] found that at 25° C. and above the organic matter in the soil decomposed more rapidly than it was formed so that the amounts present were quite low. For each fall of 10° C. in mean annual temperature the nitrogen content of the soils increased two or three times: the C/N ratio also tended to increase, and while its value in the hotter regions was about 9, in the coldest regions it was approximately 15. The humidity relations are different: as the humidity $\left(\text{he defines this as } \frac{\text{rainfall}}{\text{evaporation}}\right)$ increased the nitrogen content increased.

The organic matter may accumulate on the surface of the soil or it may mingle with the upper layers: the determining factor is the soil reaction. In neutral soils plant roots can strike down deeply (unless hindered by rock or by a water table) and earthworms move freely, dragging leaves and stems into their burrows, bringing up soil from below and leaving it on the surface where it buries any residues lying there (p. 452). In acid soils the mingling agents are less effective: earthworms are scarce or absent; and plant roots do not readily penetrate (p. 539), but tend to remain in the topmost layer where the conditions are a little more favourable.

Two cases therefore arise:—

(1) *Acid conditions:* organic matter segregates as a separate layer: this is called peat or raw humus (from the German Rohhumus).

(2) *Less acid or neutral conditions:* organic matter mingles with the soil: this is further sub-divided into:—

(*a*) Decomposition restricted so that considerable accumulation has occurred: lowland moor, fen, carr.

(*b*) Decomposition greater so that relatively small amounts are present: field humus.

[1] H. Jenny, *Soil Sci.*, 1929, **27**, 169; 1931, **31**, 247. A diagram on p. 248 of the latter paper illustrates the facts well.

In the present chapter we are concerned only with the last of these, which is far the commonest case in practice. The peats and fen soils are dealt with in Chapter IV.

The Decomposition of the Soil Organic Matter.

The organic matter thus added to the soil rapidly decomposes; the chief products are CO_2, nitrate, and soil organic matter, called for brevity humus. The decomposition is brought about by a great variety of micro-organisms living in the soil. In the main it is an oxidation; oxygen is absorbed and an approximately equal volume of CO_2 is evolved.[1] For the simpler substances, sugar, starch, etc., decomposition under aerobic conditions is rapid: for the more complex substances, however—protein, fat, possibly also cellulose—decomposition is facilitated if the first stages are at least partially anaerobic.

The Oxidation Process.—The actual amount of oxygen absorbed by soils in natural conditions has been estimated in several different ways. At Rothamsted a balance sheet is made for the organic carbon over a series of years, and the rate of loss shows that the average rate of absorption of oxygen over the year is of the order of 2 litres per square metre per day, corresponding to an evolution of about 4 grm. of CO_2. Estimates of other workers in August give higher but still comparable values: 10 to 26 litres of oxygen absorbed; 20 to 50 grm. CO_2 evolved per square metre per day. The figures are given in Table 65.

The oxidation proceeds with evolution of energy. The Broadbalk figure corresponds to some 10 calories per square metre per day. The process is thus a complete reversal of what went on originally in the plant when the organic substances were built up and energy was absorbed by means of the chlorophyll apparatus.

The oxidation, however, is not complete; a residue is

[1] First shown by Boussingault and Lévy (1853).

TABLE 65.—CO_2 EVOLUTION AND OXYGEN ABSORPTION IN NATURAL FIELD SOILS.

	CO_2 Evolved per sq. metre per day.	Oxygen Absorbed per sq. metre per day at 15° C.
	Grams.	Litres.
Broadbalk, dunged plot	4·2 [1]	2
Stoklasa and Ernest (1905) (wheat-field)	7·5 [2]	4
L.-G. Romell (1922) (August)	13-20 [3]	7-10·5
H. Lundegårdh (1925) [4] (August)	2·6-50	1·4-26
P. Hasse and F. Kirchmeyer : [5]		
Bare ground	1·6-4·8	—
Rye	5·4-10·2	—
Potatoes	11·8-12·7	—
Lucerne	9·0-21 [6]	—
H. Humfeld : [7]		
Bare ground	1·8	—
Cropped	2-4·4	—

always left, and there is also resynthesis of organic matter by the micro-organisms in building up their body substances. The substances poorest in carbon (sugar, starch, hemicelluloses, cellulose) tend to disappear first and the carbon goes more quickly than the nitrogen: the final humus is, therefore, richer both in carbon and in nitrogen than the original plant substances (Table 66).

The changes affecting the carbon and those affecting the nitrogen are intimately associated. The nitrogen can appear as nitrate only if it exceeds a certain critical amount relative to the carbon—usually if the ratio C/N is 12 or less. When the proportion of carbon is greater the excess goes off as CO_2 and the nitrogen remains as complex protein: any ammonia

[1] Annual evolution divided by 365. Stoklasa and Ernest assume only 200 "active" days, at which rate this value becomes 7·7, closely agreeing with theirs. But at Rothamsted there are more than 200 active days.

[2] Their total evolution is 13·5, but of this 6 is assumed to come from the roots of the wheat, leaving 7·5 to come from the soil.

[3] Forest soils, tree roots included. Summer values only.

[4] P. 361 of his book; see also *Soil Sci.*, 1927, **23**, 417.

[5] *Ztschr. Pflanz. Düng.*, 1927, A, **10**, 257-298.

[6] It was estimated that 80 per cent. of this was due to root respiration.

[7] *Soil Sci.*, 1930, **30**, 1 (Sept. values).

TABLE 66.—COMPARISON OF CARBON AND NITROGEN PERCENTAGES IN PLANT CONSTITUENTS AND IN SOIL HUMUS.

	Approximate Percentage Composition.		Ratio C/N.
	Carbon.	Nitrogen.	
Plant Constituents.			
Sugars	40	—	—
Cellulose, hemicelluloses, starch	45	—	—
Fats, waxes, oils	45-60	—	—
Lignin	60-63	—	—
Proteins	50	16	3
Whole Plant.			
Dry organic matter, about	45-50	1·5-3·5	15-30
Residues and stubbles—			
Cereal, about	45	0·5 or less	90 or more
Leguminous, about	50	2-3·5	13-25
Rotted Residues.			
Artificial farmyard manure	56	2·6	20
Fungus mycelium	38-48	2·5-8	6-17
Soil Organic Matter.			
As whole	58	5-6	10
Humic acid	56	5-6	10

or nitrate present is also converted into protein. When, on the other hand, the proportion of nitrogen becomes greater the excess is changed into nitrate which may be taken by plants or otherwise lost from the soil. Whatever the initial composition of the plant substances added, and whatever their form, whether straw, leaves, or animal fæces, the final humus has much the same composition and properties, and its C/N ratio in temperate regions is usually about 10-12; however this be disturbed it always comes back to its normal value. The ratio also remains unchanged during oxidation of the organic matter in arable soil; it is the same on the exhausted light land at Woburn as it was when the field was under normal cropping and receiving normal manuring (Table 67). In a detailed study of Australian soils, Hosking found that the values of the ratio were rather more variable for woodland than for grassland soils, but they tended to a steady

TABLE 67.—PERCENTAGES OF CARBON AND NITROGEN, AND C/N RATIOS IN VARIOUS SURFACE SOILS.

(Vegetable Residues C/N = about 40, but for Leguminous Residues about 25.)

(a) Old cultivated soils.

Cool Climates.	C.	N.	C/N.	Warm Climates.	C.	N.	C/N.
Rothamsted :—				Gezira (Sudan) [1] .	0·4	0·03	12·6
Broadbalk wheat: no manure since 1839 . . .	0·89	0·092	9·6	South Africa :—[2]			
Farmyard manure annually since 1843	2·91	0·263	11	Winter rainfall region	—	—	15
Woburn : 1876 . .	1·49	0·155	9·6	Transvaal:—[3]			
Woburn barley plots, 1932 :—				Black loam	1·87	0·13	14·4
No organic manure since 1876 . .	0·92	0·095	9·7	Siam :—[3]			
Farmyard manure annually since 1876	1·23	0·123	10·0	Paddy soil	6·37	0·56	11·4
Aber, N. Wales :—				Iowa [4] .	—	—	12-13
6 grass [3] . .	3·22	0·35	9·2	Average of Jenny's data [5] .	—	—	9·2
6 arable [3] . .	2·93	0·32	9·2				
50 English soils . .	—	—	10				
Poland [6] . . .	—	—	10·4				

(b) Soils recently brought into cultivation.

	C/N Ratios.	
	Washington State.[7]	Nebraska.[8]
Virgin or prairie soils . .	11·7	10·2-13·6 [9]
After cultivation . .	10·2	—
Experiment Station Farm .	—	10·1-11·0 [10]
Other cultivated soils . .	—	8·7-10·1 [9]
Farm near Elgin . . .	—	9·8-12·0 [10]

The cultivated soils had been virgin prairie 20-50 years previously.

[1] Average of forty-two samples, 1st foot, A. F. Joseph.
[2] W. E. Isaac, *Trans. Roy. Soc. S. Africa*, 1935, **23**, 205.
[3] W. McLean, *J. Agric. Sci.*, 1930, **20**, 348.
[4] P. E. Brown, *Iowa Agric. Expt. Sta. Bull.* No. 150, 1914.

[*Continuation of footnotes on opposite page.*

minimum of about 10.[1] There was no general correlation with soil type or climate.

The virgin prairie soils of North America have a C/N higher than 10, but it falls fairly rapidly when the prairie is broken up and converted into arable land, the carbon being lost more quickly than the nitrogen (Table 67, *b*). (See also pp. 378, 404.)

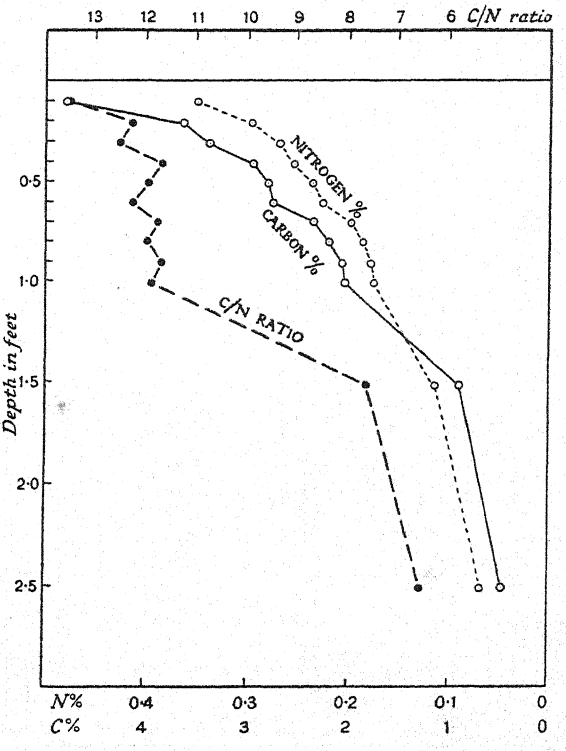


FIG. 39.—Carbon and nitrogen percentages, and carbon/nitrogen ratios, in top 3 feet of prairie upland soil, Lancaster County, near Lincoln, Nebraska (F. J. Alway and C. E. Vail, *Nebr. Agric. Expt. Sta., 25th Ann. Rept.*, 1912, pp. 145 *et seq.*).

[1] J. S. Hosking, *Soil Res.*, 1935, **4**, 253. For South African studies see W. E. Isaac and B. Gershill, *Trans. Roy. Soc. S. Africa*, 1935, **23**, Part 3.

[5] H. Jenny, *Soil Sci.*, 1929, **27**, 168. Unlike McLean he obtained lower values in warm than in cool climates.

[6] J. Kiełpiński, *Rocz. Nauk Roln.*, Poznań, 1933, **30**, 281.

[7] F. J. Sievers and H. F. Holtz, *Wash. Agric. Expt. Sta. Bull.* No. 206, 1926.

[8] F. J. Alway and C. E. Vail, *Nebr. Agric. Expt. Sta., 25th Ann. Rept.*, 1912, pp. 145 *et seq.* See also F. J. Alway, *Nebr. Agric. Expt. Sta. Bull.* No. 111, 1909.

[9] Top 12 inches.

[10] Top 6 inches.

Within the ordinary root range the C/N ratio does not alter much, but there is a sharp fall at lower depths to about 5.[1] (Table 68 and Fig. 39).

TABLE 68.—PERCENTAGES OF NITROGEN AND OF CARBON, AND C/N RATIOS AT VARIOUS DEPTHS IN BROADBALK SOIL. SAMPLED, OCTOBER, 1893 (50TH YEAR OF CROPPING WITH WHEAT). DYER, 1902.

Plot No.		2b.	2a.	3.	5.	7.
Annual Treatment, per Acre.		14 tons Farmyard Manure (200 lb. N).		Unmanured since 1839.	Full Minerals. No Nitrogen.	Full Minerals. 86 lb. N in Sulphate of Ammonia.
Depth.		Since 1843.	Since 1844.			
1st 9 ins.	C	2·23	1·58	0·89	0·93	1·10
	N	0·22	0·16	0·099	0·10	0·12
Ratio C/N		10·1	9·7	9·0	9·2	9·0
2nd 9 ins.	C	0·75	0·65	0·57	0·59	0·53
	N	0·077	0·081	0·073	0·074	0·068
Ratio C/N		9·7	7·9	7·7	7·9	7·8
3rd 9 ins.	C	0·49	0·52	0·48	0·45	0·43
	N	0·066	0·066	0·065	0·064	0·058
Ratio C/N		7·5	7·8	7·4	6·9	7·3
4th 9 ins.	C	—	—	—	0·31	0·34
	N	—	—	—	0·052	0·047
Ratio C/N		—	—	—	5·9	7·4
6th 9 ins.	C	—	—	—	0·27	0·20
	N	—	—	—	0·057	0·035
Ratio C/N		—	—	—	4·7	5·8
8th 9 ins.	C	—	—	—	0·24	0·18
	N	—	—	—	0·057	0·038
Ratio C/N		—	—	—	4·2	4·7
10th 9 ins.	C	—	—	—	0·26	0·18
	N	—	—	—	0·057	0·032
Ratio C/N		—	—	—	4·5	5·5

[1] N. H. J. Miller obtained similar values in some of the deep-seated rocks he examined. In other samples, however, there was an excess of carbon so that the ratios rose to 10 or even as high as 15 or 20 (*Quart. J. Geol. Soc.*, 1903, **59**, 133. See also A. D. Hall and N. H. J. Miller, *J. Agric. Sci.*, 1908, **2**, 343.

In consequence of the steadiness of the C/N ratio of the surface soil there is a fairly definite relation between the oxidation of the carbon and of the nitrogen once the steady state is reached in a soil: some 9 or 10 parts of carbon are oxidised for each part of nitrogen converted into nitrate. Changes in moisture or temperature conditions favourable to the action of micro-organisms increase the rate of oxidation, but the relationship between the carbon and the nitrogen is still maintained. This is illustrated by the experiments of Sievers and Holtz [1] with four widely different soils (Table 69).

TABLE 69.—DECOMPOSITION OF SOIL ORGANIC MATTER (142 DAYS).

Nitrogen in Soil, per cent.	Carbon in Soil, per cent.	C/N Ratio in Soil,	Carbon Dioxide Liberated as Carbon. mgm.	Nitrate Nitrogen Formed. Parts per Million.	Ratio of Carbon to Nitrogen Liberated by Micro-organisms from Soil Organic Matter.
0·091	0·910	10·0	119·6	15·4	7·8
0·143	1·684	11·8	187·8	18·3	10·2
0·155	1·860	12·0	167·5	17·6	9·5
0·233	2·889	12·4	230·9	26·3	8·8

It is not known how far oxidation of the nitrogen will proceed because the change is very slow. Boussingault (1873) stated that in eleven years one-third of the nitrogen of a rich soil changed to nitrate, and about one-half of the carbon to carbon dioxide.

This intimate relationship between carbon and nitrogen arises from the fact that the decomposition of the organic matter is brought about by micro-organisms. The carbohydrate substances afford them material for energy and growth, but adequate supplies of nitrogen, phosphates, and other nutrients are also needed: these are assimilated and built up into their body substances. The nitrogen takes part in the decomposition from the outset. It is assimilated by the micro-organisms that effect the decomposition, and

[1] F. J. Sievers and H. F. Holtz, *Wash. Agric. Expt. Sta. Bull.* No. 206, 1926.

converted from plant protein into microbial protein. Lyon, Bizzell, and Wilson (1918) showed that nitrate is taken up from the soil during the decomposition of plant residues con-

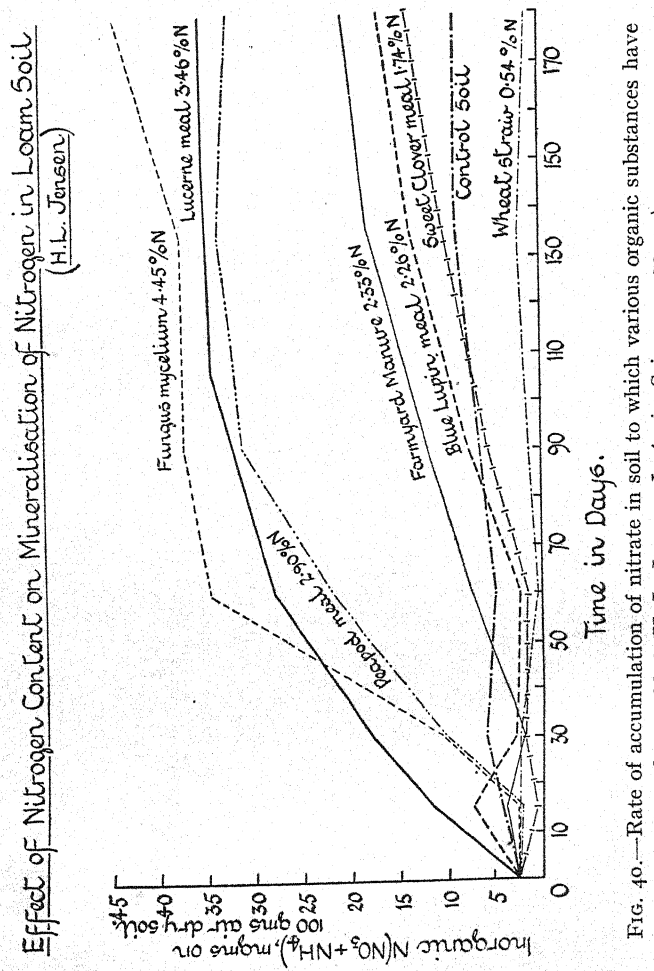


FIG. 40.—Rate of accumulation of nitrate in soil to which various organic substances have been added (H. L. Jensen, *J. Agric. Sci.*, 1929, **19**, 71).

taining less than about 1·8 per cent. of nitrogen: this amount however, seemed to keep the process self-supporting. Substances containing more nitrogen than this increased the nitrate content of the soil.

Jensen [1] found that during the decomposition of plant residues in soil part of the nitrogen nitrifies only slowly while the rest goes rapidly: the limit is 1 part of nitrogen for every 20 or 25 parts of carbon when the soil is neutral and for every 13 to 18 parts when it is acid: only where there is an excess of nitrogen above this amount does nitrate appear.[2] His results are shown in Fig. 40.

Many investigations have been made to follow the course of the decomposition: three only need be mentioned here.

Du Toit at Rothamsted [3] mixed plant residues in the soil and after six months ascertained the percentage loss of the various constituents, and also the gain in the soluble humus. The furfuroids disappear almost completely, but the cellulose and lignin to a much less extent. The loss of lignin was closely related to the gain of humus; over the whole of his determinations Du Toit concluded that 2·5 parts of lignin form 1 part of humus, a figure almost identical with that obtained in the laboratory by Schrader [4] when lignin is converted by alkali into an artificial humus.

An extensive series of investigations made by Waksman and Tenney [5] showed that the celluloses and hemicelluloses decomposed fairly completely, but lignin did not. Protein also remained, but they showed that this was largely re-synthesised by micro-organisms (p. 344):—

[1] H. L. Jensen, *J. Agric. Sci.*, 1929, **19**, 71.

[2] This is important in the use of farmyard manure. In order to avoid the immobilisation, H. Krantz treated the manure in a special way to give "Edelmist." The process is described by A. Cunningham in *Scot. J. Agric.*, 1927, **10**, 434; the bacteriological studies were made in F. Löhnis's and G. Ruschmann's laboratories (*Bied. Zbl.*, 1931, A, **60**, 177). See B. Niklewski, *Ztschr. Pflanz. Düng.*, 1935, **37**, 92; H. Glathe and A. Cunningham, *J. Agric. Sci.*, 1933, **23**, 541.

[3] M. M. S. du Toit and H. J. Page, *ibid.*, 1930, **20**, 478. The work was done in 1925 and recorded in the 5th ed. of *Soil Conditions* (1926), but separate publication was inadvertently delayed.

[4] *Brennstoff-Chem.*, 1922, **3**, 161.

[5] *Soil Sci.*, 1927, **24**, 275 and 317; **26**, 155.

	Plant Material.	Soil Organic Matter.
Celluloses . . .	20–40	3–5
Hemicelluloses . .	15–25	5–8
Lignin . . .	10–30	40–50
Protein . . .	2–10	30–35
Water-soluble protein	15–30	Nil

It is difficult to follow the changes in the soil, and A. G. Norman [1] adopted the simpler method of studying under laboratory conditions the rotting of cereal straw, which, having a low C/N ratio, decomposes easily only when more nitrogen is added to it. The two most striking changes were :—

(1) The rapid decomposition of the cellulose and the hemicelluloses.

(2) The synthesis by micro-organisms of protein from the ammonia or nitrate supplied in the culture medium.

The cellulose decomposes to a considerable extent, and this accounts for most of the loss of weight. Decomposition, however, is not complete because some of the cellulose is protected by a resistant coating of lignin. The hemicelluloses decompose rapidly at first contributing no doubt largely to the heat evolution : further, their decomposition facilitates the development of a very mixed flora that subsequently attacks the cellulose : the decomposition, however, is not complete and at a certain level no further loss occurs. This suggests an equilibrium, and there was indeed evidence of re-synthesis of hemicellulose by the micro-organisms. Lignin, on the other hand, does not suffer serious loss unless decomposition continues for a long time.

Heterotrophic and Autotrophic Organisms.

The various changes involved in the decomposition of the organic matter fall into two broad groups. In the early stages of the decomposition the organic matter is still so complex

[1] *Ann. Appl. Biol.*, 1931, 18, 244.

and contains so much available energy that it serves direct as sources of food and energy to the micro-organisms. These therefore are called heterotrophic, since they obtain these essential requirements from outside sources. In the last stages the products are CO_2, ammonia or nitrogen, sulphur; all simple and containing no readily available energy, so that they are quite unsuitable for the heterotrophic organisms. These substances are, however, utilised by the second group of organisms, which are able to synthesise their cell substance from CO_2 just as green plants do, but unlike green plants they are not dependent on sunlight as their source of energy: instead they utilise the energy of some simple chemical reaction, the oxidation of ammonia, of sulphur, etc. These organisms are therefore called autotrophic, being dependent on their own activities for the synthesis of the food-stuff, and the process is called a chemosynthesis as distinct from the plant photosynthesis. The distinction was recognised by Winogradsky, whose investigations will repeatedly be mentioned later: the names are due to Pfeffer.

The Micro-Organisms Concerned in the Process.

All the micro-organisms active in the soil are in some way connected with the decomposition of the organic matter, for it is on this that they all depend for food and energy. Some, however, play a more direct and more special part than others, so that they are particularly associated with one group of compounds or activities.

Sugars and Starch.

These are decomposed by a considerable proportion of the organisms in the soil under all conditions: there is nothing specific about the action. The final products are CO_2 and water; Jensen,[1] however, showed that certain fungi produce humus. The soil nitrate is assimilated and converted into microbial protein (pp. 344, 350).

[1] H. L. Jensen, *J. Agric. Sci.*, 1931, **21**, 38 and 81.

Cellulose.

Cellulose, on the other hand, is attacked only by a limited number of organisms, and each group works only under a somewhat narrow range of conditions. Jensen at Rothamsted found that the flora developing on addition of farmyard manure, straw, or cellulose (filter paper) to soil, and therefore presumably most concerned in the decomposition, was governed by the reaction and the air supply :—

Acid conditions: *p*H 4 or less. Mostly fungi,[1] especially *Trichoderma* and *Penicillium*.

Less acid and neutral conditions: *p*H 5·5 and more. Mostly bacteria.

(1) Aerobic.

*p*H 5·5-6: bacteria. Hutchinson and Clayton's Spirochæte.

*p*H 7: Vibrios. Small rods of Gray and Kalninš. Mostly non-spore formers, but a few spore formers. Some fungi : *Mycogone nigra*, *Stachybotrys sp.* Certain myxobacteria.

(2) Anaerobic.

Clostridia (spore formers) *Coccospora agricola* (?), *Botryosporium sp.*

Aerobic Conditions.—Jensen obtained the same relationship between *p*H value and decomposition flora whether he investigated natural soils of varying acidity or worked with one soil and varied its reaction by adding lime. It was formerly supposed that actinomycetes played an important direct part in the decomposition of cellulose. They certainly can decompose it in culture solutions,[2] but Jensen found no evidence of any increase in their number when cellulosic materials were added to the soil at Rothamsted, nor did Waksman and Skinner at New Jersey ;[3] they multiplied later, however, when

[1] See also R. J. Dubos, *J. Ecology*, 1928, **9**, 12.
[2] A. Krainsky, *Zbl. Bakt.*, Abt. II, 1914, **41**, 649.
[3] S. A. Waksman and C. F. Skinner, *J. Bact.*, 1926, **12**, 57.

the fungus mycelium began to disintegrate. J. Ziemięcka,[1] using her modification of Cholodny's method, also observed this secondary development of actinomycetes.

Soil fungi capable of decomposing cellulose have long been known. They were first studied by van Iterson,[2] later by McBeth and Scales,[3] by Waksman and Skinner,[4] and by Jensen ;[5] further investigation is still needed into the fungi that predominate in acid conditions. H. Felsz-Karnicka[6] studied cellulose decomposition in both acid and neutral soils from the experimental fields at Sobieszyn, Poland. In the acid soils the process was effected entirely by fungi, no less than thirteen different species, mostly *fungi imperfecti* and ascomycetes, taking part. Their numbers were highest and the flora was most varied on the plots manured with sulphate of ammonia, and lowest on those that had received lime: the rate of decomposition of the cellulose was related to the numbers present. In neutral soils, on the other hand, the decomposition was brought about by bacteria, and it was much more rapid than on the acid soils.

Waksman found that the whole of the cellulose not assimilated by the fungi was converted into CO_2; no by-products could be detected.[7] Jensen, on the other hand, found that some fungi produced humus during the decomposition of cellulose, though others did not. Fungi seem to be the chief agents effecting the decomposition of straw. A succession of organisms appears to act, and the synthesised microbial protein is utilised over and over again. In manure heaps many of the common fungi occur: particularly Aspergillus, Penicillia

[1] *Rocz. Nauk Roln.*, 1934, **33**, 23.

[2] *Zbl. Bakt.*, Abt. II, 1904, **11**, 689.

[3] *U.S.D.A. Bur. Plant Ind. Bull.* No. 266, 1913.

[4] *J. Bact.*, 1926, **12**, 57.

[5] H. L. Jensen, *J. Agric. Sci.*, 1931, **28**, 38, 81; S. A. Waksman, *Arch. Mikrobiol.*, 1931, **2**, 136; A. G. Norman, *Ann. Appl. Biol.*, 1931, **18**, 244.

[6] Halina Felsz-Karnicka, *Puławy Memoirs*, No. 240, 1935, **16**.

[7] H. Heukelekian and S. A. Waksman, *J. Biol. Chem.*, 1925, **66**, 323.

and Trichoderma: they are active at temperatures higher than usual in the soil. In the manure heaps the flora is, as one would expect, thermophilic, and includes several aspergilli (*fumigatus*, *nidulans*, *niger*, *terreus*), several actinomycetes, a Trichoderma, and Sepedonium: all these act at relatively high temperatures; the last named has its optimum temperature at 45° C. to 50° C., and it still survives at temperatures exceeding 60° C., these being far above the usual range. Most soil organisms have their optimum at about 22° C. and fail to grow above about 35° C.

These organisms are not only thermophilic but are strongly thermogenic, and when inoculated on to sterile straw they decompose it so effectively that they rapidly raise the temperature to 40° C. or more.[1]

It is not known how far these organisms are effective in the soil.[2] The bacteria that function in less acid, and in neutral conditions fall into three groups.

(1) The organism that predominates between *p*H 5·5 and 6 was first described by Hutchinson and Clayton [3] and called by them *Spirochæta cytophaga:* it is now known as *Cytophaga hutchinsoni*. It is aerobic and very selective in its action, cellulose being the only compound on which it will grow: it is indeed inhibited by many carbohydrates, especially those containing reducing groups. Its nitrogen requirements are met by simple compounds, such as ammonium salts, nitrates, amino-acids, but not by higher compounds, such as peptone (except in weak solution), gelatine, etc. The products of decomposition of cellulose include small quantities of volatile acids[4]; mucilage soluble in ammonia but insoluble in acids, and yielding no optically active compounds on hydrolysis; and a pigment apparently related to the carotin group. There is no obvious gas in the cultures. Like many other soil

[1] A. G. Norman, *Ann. Appl. Biol.*, 1930, **17**, 575.

[2] See also R. D. Rege, *ibid.*, 1927, **14**, 1.

[3] H. B. Hutchinson and J. Clayton, *J. Agric. Sci.*, 1919, **9**, 143.

[4] See also S. Śnieszko, *Acta Soc. Bot. Poloniae* (Warsaw), 1934, **11**, 84.

organisms, it passes through a life cycle, the stages of which show considerable morphological differences.

Winogradsky regards this not as an individual but as a group which he has divided into a number of different species.[1]

(2) The vibrios, small rods, non-spore formers.—These were found by the earlier investigators, van Iterson and McBeth and Scales. The first to be described in detail was the *Microspira agar-liquefaciens* of P. H. H. Gray and C. H. Chalmers,[2] working at Rothamsted. This organism differs from the spirochæte both morphologically and in the important property of being more tolerant of other carbohydrates, its power of destroying cellulose being, indeed, enhanced by small quantities of dextrin, xylose, arabinose, and certain other sugars, and also of lignin ; unlike most other organisms it liquefies agar. It resembles *Cytophaga hutchinsoni* in utilising ammonia and nitrate as nitrogenous nutrients. Subsequently Kalninš,[3] also at Rothamsted, isolated and studied in detail some twenty different forms of various types, including one that converts about 50 per cent. of the cellulose into glucose or a sugar very like it. Jensen [4] isolated a few more. Kalninš also found a few spore formers, the first of the kind known to decompose cellulose aerobically.

(3) Myxobacteria.—Helena and Seweryn Krzemieniewski [5] have shown that some myxobacteria (p. 429) (*Sorangium* spp.) found in various soils rapidly decompose cellulose aerobically. The organisms utilise ammonium salts and nitrates as sources of nitrogen, but they are strictly aerobic and cannot assimilate the oxygen from nitrates in absence of air. Two species—*S. compositum* and *S. nigrescens*—have been obtained pure, and their reactions have been studied in detail.

Anaerobic Conditions.—Anaerobic decomposition occurs naturally in swamps and marshes, and is characterised by the

[1] *Ann. Inst. Pasteur*, 1929, **43**, 549.
[2] *Ann. Appl. Biol.*, 1924, **11**, 324.
[3] *Latv. Univ. Raksti., Lauks. Fak.*, 1930, Ser. 1, **11** (*Roth. Mem.*, Vol. 16).
[4] *J. Agric. Sci.*, 1931, **21**, 38.
[5] Private communication.

production of methane, which thus derived its old name marsh gas. It was first systematically investigated by Dehérain in 1884,[1] and shown to be brought about by bacteria which, however, are dependent on the presence of nitrogen compounds. It can proceed in either of two ways, giving respectively marsh gas and hydrogen: the latter, however, being always associated with the formation of butyric acid. He suggested that there were two distinct micro-organisms, one producing marsh gas and the other hydrogen, or alternatively, one organism capable of producing either gas as the conditions varied. Eleven years later, when bacteriology had advanced considerably, Omeliansky was able to show that there are, in fact, two separate organisms. Both organisms require the same general conditions of air exclusion, ample supply of water and nitrogen compounds. They differ in their reaction requirements; the hydrogen organism requires an acid and the marsh gas organism a neutral medium. The fermentation can therefore be changed over to either direction by controlling the acidity.[2]

Neither of Omeliansky's organisms has yet been isolated in a pure condition, but there is no doubt about the general accuracy of the work.

Other anaerobic organisms capable of decomposing cellulose have since been discovered. In 1923 Mme. Y. Khouvine discovered[3] in human intestines an organism which she associated

[1] *Ann. Agron.*, 1884, **10**, 385; see also 1888, **14**, 97, where he discusses the decompositions in a manure heap.

[2] In neutral conditions considerable quantities of gas are obtained by fermentation of straw or other plant tissues. E. H. Richards and R. L. Amoore have obtained at Rothamsted quantities of gas corresponding to 10,000 cubic feet per ton of vegetable material (material from the Nile Sudd was used); the gas contained 38 per cent. CO_2, 56 per cent. methane, and 6 per cent. other combustible gas, mainly hydrogen, representing about one-third of the energy (calorific power) of the fermented material. In acid conditions evolution of gas is much slower, but it contains up to 55 per cent. hydrogen, the rest being chiefly carbon dioxide. For another set of figures, which are not dissimilar, see A. M. Buswell, *J. Ind. Eng. Chem.*, 1930, **22**, 1168.

[3] *Ann. Inst. Pasteur*, 1923, **37**, 711.

with the digestion of cellulose there: she called it *Bac. cellulosæ dissolvens*. Three years later, in 1926, Viljoen, Fred, and Peterson [1] described another organism, the thermophilic *Clostridium thermocellum*, which decomposes cellulose under anaerobic conditions between the temperature range 43° C. and 65° C.; it continues to live at 72° C., though it no longer decomposes cellulose at that temperature, nor does it below 40° C., so that it seems hardly likely to act in the soil. This culture, however, is now recognised to be an association of three organisms, only one of which actually decomposes cellulose, but its activity is much enhanced in presence of the other two. More recently H. Glathe and A. Cunningham have shown that anaerobic organisms capable of decomposing cellulose occur in Edelmist (p. 351).[2]

Whatever organisms attack the cellulose, their speed of action depends on the amount of nitrogen present: this fact is utilised in the process of making artificial farmyard manure.[3] Waksman and Skinner [4] show that less nitrogen is required under anaerobic than under aerobic conditions, because of the smaller amount of energy utilised by the organisms: decomposition is, however, slower in starting. This is well illustrated in Acharya's experiments:[5] 100 grm. of rice straw in decomposing required the following amounts of nitrogen:—

Anaerobic conditions .	0·07 grm.
Water-logged conditions .	0·39 ,,
Aerobic conditions . .	0·54 ,,

Hemicelluloses.

The hemicelluloses are polysaccharides containing both hexose and pentose groups, and frequently uronic acid units (either glycuronic or galacturonic units), though as the

[1] *J. Agric. Sci.*, 1926, **16**, 1.

[2] H. Glathe and A. Cunningham, *ibid.*, 1933, **33**, 541.

[3] H. B. Hutchinson and E. H. Richards, *J. Min. Agric.*, 1921, **28**, 398 and 482.

[4] *J. Bact.*, 1926, **12**, 57.

[5] C. N. Acharya, *Biochem. J.*, 1935, **29**, 1116.

carboxyl group is involved in linkage they possess no acid properties. They are readily attacked by many fungi, for which, indeed, they appear to be as effective nutrients as glucose.[1]

Bacteria, on the other hand, have little power to decompose hemicelluloses, though many of the common soil forms can do this to a small extent.

Xylans.

The decomposition of xylans, like that of celluloses, is brought about by fungi in acid soil conditions and by specific bacteria in neutral conditions. J. Ziemięcka[2] studied a new species, *Bac. xylanophagus*, which is the chief agent in neutral soils: it assimilates 3-5 parts of combined nitrogen for each 100 parts of xylan decomposed, and it can bring about denitrification. It produces CO_2 and a colloidal residue, and its development is followed by a secondary growth of moulds.

Lignin.

Lignin is by far the most resistant of all plant constituents, nevertheless it suffers some decomposition in the soil.[3] Much of the older work is vitiated by the use of faulty methods of estimation, and there is no clear evidence of decomposition in the soil in short periods of two or three months. After longer periods, however, some decomposition is effected; under aerobic conditions some 40-50 per cent. of the lignin of oat straw disappears in a year and 50-60 per cent. in eighteen months. Under anaerobic conditions, however, decomposition is slower.

Nothing definite is known of the organisms decomposing the lignin. All laboratory experiments with isolated lignin

[1] A. G. Norman, *Ann. Appl. Biol.*, 1934, **21**, 454.

[2] *Rocz. Nauk Roln.*, 1931, **25**, 313; *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 167.

[3] For a summary of the present position see A. G. Norman, *Sci. Prog.*, 1936, **119**, 442.

have failed; indeed there is some evidence that lignin may exert a certain bacteriostatic effect. Waksman [1] states that actinomycetes and bacteria are concerned in the decomposition in soil.

Certain basidiomycetes can decompose lignin in wood, but they do not occur in the soil.

Aromatic Plant Constituents, Phenols, and other Carbon Compounds.

Certain plant constituents and some of the decomposition products of proteins are poisonous to plants and would cause serious injury if they should accumulate in the soil. Fortunately they do not; those capable of oxidation with evolution of energy are decomposed by micro-organisms. The commonest occurring in nature are the phenols and their derivatives, and certain aromatic aldehydes, vanillin, etc. Fowler, Ardern, and Lockett [2] were the first to show that phenol could be decomposed by bacteria and to isolate and describe the organisms. In the course of an investigation on sewage they had observed a disappearance of phenol from effluents in circumstances strongly suggesting biological activity. R. Wagner [3] found many organisms in soil capable of oxidising and utilising as sources of energy phenol, benzene, toluene, xylene, catechol, phloroglucinol, and similar compounds: this has been confirmed by various workers at Rothamsted. Owing to its technical importance (p 477), the decomposition of phenol has been studied in detail by N. N. Sen Gupta.[4] The action is complex, including a chemical change brought about apparently by the manganese dioxide in the soil and an oxidation effected by bacteria. P. H. H. Gray and H. G. Thornton found several kinds of bacteria in

[1] *Principles of Soil Microbiology*, 1st ed., 1927, pp. 298 and 459. See also Waksman and I. J. Hutchings, *Soil Sci.*, 1936, **42**, 119.

[2] *Proc. Roy. Soc.*, 1911, B, **83**, 149.

[3] *Ztschr. Gärungsphysiol.*, 1914, **4**, 289.

[4] *J. Agric. Sci.*, 1925, **15**, 497.

English soils that can oxidise phenol, *o*-, *m*-, and *p*-cresol, toluene, and naphthalene. It is difficult to understand how they should have acquired this remarkable power, as neither toluene nor naphthalene occurs naturally, and both are particularly difficult to split up chemically at ordinary temperatures.

Gray [1] also found two bacteria, and Kluyver [2] a mycobacterium, which attack indol, a constituent of farmyard manure and urine, oxidising it to indigotin. These organisms use the indol as a source of nitrogen but not of energy; they need, therefore, sugar or similar compounds as well. It is, however, not the ideal nitrogenous nutrient for them, and they grow more rapidly when supplied with other nutrients instead.

The oxidation of vanillin by bacteria in the soil is of some interest, as this substance occurs in certain plant residues and would be toxic if it accumulated.[3] Numerous aromatic compounds were found by Mrs. A. Matthews to cause great increases in bacterial numbers in the soil [4] with simultaneous assimilation of ammonia, and presumably, therefore, served as food or energy material. Organisms decomposing the paraffins and cyclic hydrocarbons have been described by V. O. Tausson.[5]

Keratin, a complex protein rich in cystine, the amino-acid characterised by the presence of much sulphur, comes into the soil from animal sources, being an important constituent of horns, hoofs, nails, feathers, hair, epithelial cells, etc. Jensen [6] shows that it is decomposed by two soil organisms, strains of actinomycetes, one being *A. citreus* Krainsky, the

[1] *Proc. Roy. Soc.*, 1928, B, **102**, 263.

[2] *Nederl. Tijdschr. Hyg. Microbiol.*, 1929, **3**, 308.

[3] See W. J. Robbins and E. Lathrop, *Soil Sci.*, 1919, **7**, 475; W. J. Robbins and A. B. Massey, *ibid.*, 1920, **10**, 237; and M. J. Funchess, *Ala. Agric. Expt. Sta. Bulls.* Nos. 195 and 196, 1917; R. C. Collison, *J. Amer. Soc. Agron.*, 1925, **17**, 58.

[4] *J. Agric. Sci.*, 1924, **14**, 1. See also W. Buddin, *ibid.*, 1914, **6**, 417.

[5] E. E. Uspensky, *Soil Microbiology in the U.S.S.R.*, Moscow, 1933.

[6] *J. Agric. Sci.*, 1930, **20**, 390-398.

other resembled *A 145* Waksman. The sulphur appears as a mercaptan or as hydrogen sulphide which is then attacked by the sulphur bacteria (p. 400).

Decomposition of Microbial Tissue.

The decomposition of organic matter is accompanied by the synthesis of microbial and particularly fungal tissue. This was supposed by the older workers [1] to be very resistant to decomposition, but later investigations show that it is not. Decomposition of the higher fungi, such as *Polyporus*, appears to proceed as rapidly as that of other organic materials of similar nitrogen content, and to be equally governed by the C/N ratio of the tissues.[2] The tissue of soil fungi appears also to decompose completely.[3] On the other hand, Jensen,[4] working with farmyard manure, found that while part of the fungal tissue nitrified rapidly, a residue appeared to be highly resistant; also there was no relation with the C/N ratios. He further found that the structural constituent, chitin, a supposedly resistant substance forming 20-25 per cent. of the fungal tissue, is readily decomposed. Some fungal tissue contains a high percentage (20-30 per cent.) of fatty constituents which somewhat retard decomposition.

The Changes in the Nitrogen Compounds.

I. The Formation of Ammonia and Nitrate.

Ammonia Production.

The nitrogen compounds in plant residues added to the soil break down to form ammonia so long as the ratio of C/N does not much exceed 10.

The investigations by Marchal (1893) of the method of ammonia production in the soil are so complete that little

[1] *E.g.* F. Löhnis, *Handbuch der Mikrobiologie*, 1st edn.
[2] A. F. Heck, *Soil Sci.*, 1929, **27**, 1.
[3] A. G. Norman, *Ann. Appl. Biol.*, 1933, **20**, 146.
[4] *J. Agric. Sci.*, 1932, **22**, 1.

has since been added to the facts he ascertained. Müntz and Coudon (1893) had established the micro-organic nature of the process by showing that it was stopped by sterilisation; this result, however, is not quite correct. Marchal, therefore, made systematic bacteriological and mycological analyses of soils, and studied the action of the organisms thus obtained on solutions of albumin. Of the dozen or so varieties that invariably occurred, practically all decomposed the albumin and formed ammonia. One of the *mycoides* group proved very vigorous and was studied in some detail. The process was considered to be a simple oxidation necessary to the life of the organism; oxygen was absorbed and carbon dioxide evolved, the ratio $NH_3 : CO_2$ produced being 1 : 8·9. For complete oxidation of the carbon, hydrogen, and sulphur of the albumin molecule the ratio would be 1 : 10·3; but the change was known to be incomplete, and small quantities of leucine, tyrosine, and fatty acids, could also be detected. Free oxygen, however, was not essential. When grown in a culture solution containing sugar and nitrate the organism took its oxygen from the nitrate, but it still produced ammonia.

The energy relationships thus indicated were wholly overlooked by investigators for nearly a quarter of a century: it was not till 1916 that Doryland showed their significance. The organism produces ammonia, not because it must, but because it thereby obtains its prime requirements, nutrients and energy, and can still leave ammonia in excess of its needs. If sources of energy other than proteins are supplied, *e.g.* carbohydrates, ammonia production may fall to nothing or become negative: the ammonia producers then become ammonia absorbers just like the higher plants, and indeed they compete with growing crops.

This is an important factor causing the small variations in the C/N ratio of soils. It explains also the incompleteness of the recovery of ammonia from organic compounds first observed by J. G. Lipman of New Jersey in the intensive series of vegetation experiments begun in 1898 and described

in the Annual Reports of the Station.[1] Putting the recovery of ammonia from sulphate of ammonia as 100, the recovery from dried blood was 90 and that from fresh farmyard manure only 75. It further explains why the production of ammonia from dried blood is decreased by carbohydrates.[2]

The Organisms Concerned.—The production of ammonia in soil was for long attributed to the large spore-forming groups *B. mycoides* and *B. subtilis*, for the reason that they predominated on the old gelatine plates. H. J. Conn,[3] however, obtained evidence from platings that these organisms play no important part in the soil; the active agents were the smaller non-sporing forms of the *Ps. fluorescens* group and another that he called *Ps. caudatus*, which, while not very numerous in unmanured soil, multiply vigorously on addition of farmyard manure and produce ammonia. The modern direct methods of counting confirm this view to the extent that they show a large numerical superiority of the non-sporing forms in field soils, but they show also the presence of vegetative stages of the spore formers which can multiply in suitable conditions. Interest in *B. mycoides* has recently been revived in Russia, where it is regarded by Jashnova, Tyagny-Ryadno [4] and others as the chief ammonia producer in the soil. It also assimilates ammonia and takes up most of what it produces if nitrification is for any reason slowed down too much. So long as the nitrifying organisms can act, however, they get the ammonia because they can take it up at lower concentrations than is possible for the *B. mycoides*. Low temperature is very unfavourable to its activity. It tolerates considerable acidity; it can produce organic acids from carbon compounds and it can readily dissolve enough mineral phosphate for its requirements. It

[1] For a summary 1898-1912 see *N.J. Agric. Expt. Sta. Bull.* No. 288, 1916, and with A. W. Blair (1915).

[2] J. G. Lipman, A. W. Blair, I. L. Owen, and H. C. McLean, *ibid.*, No. 247, 1912.

[3] *N.Y. St. Agric. Expt. Sta. Tech. Bull.* No. 67, 1919.

[4] M. Tyagny-Ryadno, *J. Agric. Sci.*, 1933, **23**, 335.

is present in quantity in farmyard manure: indeed Tyagny-Ryadno suggests that one of the advantages of using farmyard manure is to ensure a good inoculation of the soil with *B. mycoides*.

There is some evidence that actinomycetes and fungi can produce a certain amount of ammonia in soils.

Ammonia production in soil, however, is not entirely the result of direct action of micro-organisms. It goes on even in presence of antiseptics: presumably, therefore, enzymes are in part responsible (Russell and Hutchinson [1]). Subrahmanyan (1927, 1928) showed that an aqueous glycerine extract of toluened soil liberated ammonia from peptone, and therefore presumably contained a deaminase. He has obtained evidence that this causes the accumulation of ammonia which takes place in water-logged soils.

There is an important difference between amides and amino-compounds as sources of ammonia: the former split it off easily by hydrolysis, the latter only after drastic decomposition.

Nitrification.

The ammonia formed by the action of soil bacteria, or added in manures, is changed to carbonate, which is then rapidly converted into nitrite, and this into nitrate, the changes proceeding so rapidly that only traces of ammonia or nitrite are ever found in normal arable soils.[2] We may, therefore, infer that the production of nitrites is slower than that of nitrate, while the formation of ammonia is slower still and sets a limit to the speed at which the process can take place. Thus a measure of the speed at which nitrates are formed in soil does not measure the rate of nitrification as is sometimes assumed, but the rate of ammonia production.[3]

A further interesting point is that the action becomes more restricted as it progresses. The first stage, the formation of

[1] *J. Agric. Sci.*, 1909, **3**, 111.
[2] E. J. Russell, *ibid.*, 1910, **3**, 233-245.
[3] See also P. L. Gainey, *Soil Sci.*, 1917, **3**, 399-416.

ammonia, can be brought about in a variety of ways and by many different micro-organisms; the second stage, the oxidation of ammonia to nitrate is a less general property of micro-organisms, though it can still be accomplished to a greater or less extent by a good number of them, and possibly even by non-biological processes; the final stage, however, the oxidation of nitrite to nitrate can apparently only be accomplished by micro-organisms [1] and only by very few of them.

The essential facts of nitrification are readily demonstrated, by putting a small quantity of soil—0·02 to 0·05 grm.—into 50 c.c. of a dilute solution of ammonium sulphate containing nutrient inorganic salts and some calcium or magnesium carbonate, but no other carbon compound.[2] After three or four weeks at 25° the ammonia has all gone and its place is taken by nitrates. The conversion is almost quantitative, only an insignificant quantity of nitrogen being retained by the organisms.

The first stage, the production of nitrite, can be brought about by a number of organisms, though only few can do it to any important extent. N. R. Dhar, G. G. Rao,[3] and others in India, de' Rossi [4] in Italy and A. S. Corbet at Jealott's Hill [5] support the view that it can also be effected by purely chemical processes under the influence of sunlight or ultra-violet light, but

[1] A. S. Corbet considers that it can be accomplished non-biologically if the *p*H is below 5 (*Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 133).

[2] Omeliansky (1899) used 2 grm. each $(NH_4)_2SO_4$ and NaCl, 1 grm. KH_2PO_4, 0·5 grm. $MgSO_4$, 0·4 grm. $FeSO_4$ in 1 litre of water, and added 0·5 grm. $MgCO_5$ for each 50 c.c. of solution used. Nitrite formation goes on in this solution. For nitrate production he used 1 grm. each $NaNO_2$ and Na_2CO_3, 0·5 grm. each KH_2PO_4 and NaCl, 0·4 grm. $FeSO_4$ and 0·3 grm. $MgSO_3$ in 1 litre of water. S. F. Ashby (*Trans. Chem. Soc.*, 1904, **85**, 1158, and *J. Agric. Sci.*, 1907, **2**, 52) found that both processes went on simultaneously when he diluted the first of these solutions to one quarter the strength.

[3] G. Gopala Rao and N. R. Dhar, *Soil Sci.*, 1931, **31**, 379; 1934, **38**, 143.

[4] G. de' Rossi, *Ann. Tec. Agrar.*, 1935; *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 135.

[5] A. S. Corbet, *Biochem. J.*, 1934, **28**, 1575.

their critics object that the nitrite test is so sensitive and the possibilities of contamination so numerous, that rigid proof of chemical oxidation is exceedingly difficult to obtain.[1]

The first of the nitrite-forming bacteria to be isolated was the *Nitrosomonas* discovered by Winogradsky in a brilliant investigation in 1899.[2] Previous investigators had attempted to grow the nitrifying organisms on gelatine plates, and had failed because the organisms will not tolerate gelatine : glucose, peptone, and other organic substances are also harmful (Winogradsky and Omeliansky, 1899). Winogradsky recognised that the organisms obtain their carbon from carbon dioxide, and prepared a silica jelly free from organic matter on which they could grow sufficiently well to enable him to isolate and study them. The proof that carbon dioxide is the source of their carbon was made more rigid by Godlewsky, who showed that nitrification proceeds in solutions free from organic matter so long as the air supplied contained carbon dioxide, but stops as soon as the carbon dioxide is removed by passage over caustic potash.[3] But the synthesis of complex cell substances from carbon dioxide is an endothermic process requiring a supply of energy. In the case of the green plant, the energy comes from light, the transformer being chlorophyll. Here, however, light is out of the question, and is even fatal to the organism. Winogradsky (1890) suggested that the necessary energy is afforded by the oxidation of ammonia and of the nitrite, and he traced a definite relation between the amount of ammonia oxidised and the carbon assimilated. Expressed in atomic units, the ratio C/N was approximately 36. The value is really somewhat higher, but even so only about 5 per cent. of the energy liberated in oxidising the ammonia is utilised in the synthesis of protoplasm from CO_2.

[1] N. V. Joshi and S. C. Biswas, *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 104.

[2] Winogradsky's classical organisms have recently been fully described by T. Y. Kingma Boltjes, " Onderzoekingen over nitrificeerende bacteriën ": *Thesis*, Delft, 1934, and *Arch. Mikrobiol.*, 1935, **6**, 80.

[3] Quoted in Lafar, *Tech. Mykologie*, 1906, **3**, 165.

For a long while *Nitrosomonas* and a closely allied *Nitrosococcus* were the only organisms known that could oxidise ammonia to nitrite. This was a source of great difficulty, because the organisms do not tolerate organic matter, nor are they tolerant of acidity, yet nitrification proceeds in acid soils and in soils rich in organic matter, and even in manure heaps, nitre beds, and activated sewage sludge.[1] The explanation of the difficulty is afforded by the discovery by Cutler [2] at Rothamsted of species of soil micro-organisms capable of producing nitrites from various ammonium salts, but differing completely from *Nitrosomonas* and *Nitrosococcus* not only morphologically, but also in that they need organic matter and tolerate a considerable degree of acidity (*p*H 4·8). They were first found in the effluent from a sugar beet factory and then shown to be commonly distributed in soils. Many soil organisms possess to a slight extent this property of forming nitrites. Using an ingenious modification of her father's silica jelly plates, which she enamelled with a layer of calcium and magnesium carbonates or powdered kaolin and then sprinkled with soil particles, Helen Winogradsky has isolated some new and potent nitrite formers: five strains of *Nitrosomonas* differing morphologically and physiologically; a spirochæte, and a group of cystic or zoogleal organisms called *Nitrosocystis* characterised by great sensitiveness to the presence of iron in the medium and growing only when sufficient is available to them. They occur in quantity in the activated sewage sludge from the purification plant at Colombes, in which nitrification proceeds far more rapidly than in soil.[3] Winogradsky suggests that the gelatinous sheath acts as a filter, keeping out the large

[1] For studies of nitrification on sewage filters see H. Chick, *Proc. Roy. Soc.*, 1906, B, **77**, 241; in manure heaps, B. Niklewski, *Zbl. Bakt.*, Abt. II, 1934, **90**, 193; in nitre beds, Müntz and Lainé, *Ann. Inst. Nat. Agron.*, 1907, II, **6**, 15; N. V. Joshi, *Agric. J. India*, 1925, **20**, 20.

[2] D. W. Cutler and B. K. Mukerji, *Proc. Roy. Soc.*, 1931, B, **108**, 384.

[3] *Ann. Inst. Pasteur*, 1933, **50**, 350; *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 138. See also W. Swederski, *Puławy Memoirs*, 1934, **15**, 158.

organic molecules, and permitting only small simple molecules or electrolytes to penetrate to the organism.

The chemical course of the oxidation is unknown. Beesley showed that the ammonia disappears before it is converted into nitrite so that the sum of ammonia + nitrite first falls considerably below the amount of ammonia originally present and then rises to about 90 per cent. of the original quantity.[1] Whether the ammonia is first assimilated by the organism or converted direct into hydroxylamine has never been rigidly proved; Beesley, and also Mazé,[2] incline to the latter view. A. S. Corbet [3] found hyponitrous acid in some cultures and suggests that the stages are hydroxylamine → hyponitrite → nitrite.

Nothing is known of the mechanism of the oxidation. Neither Omeliansky (1899) nor Bonazzi could find any evidence of an oxidase or peroxidase in *Nitrosomonas* or the culture solution. Bonazzi [4] showed that the trace of iron salt essential to the process is reduced from the ferric to the ferrous state, and he suggests that it acts as the carrier of oxygen on lines similar to those assumed by Bach and Chodat for green plants.

The last stage of nitrification, the conversion of nitrite to nitrate, is more rapid and more specific than the others, being restricted to a very few organisms. The *Nitrobacter* originally isolated by Winogradsky remains the most important. He and his daughter have lately found another organism *Bactoderma alba* capable of bringing about this change, also a group of organisms—*Nitrocystis*, but no others are as yet known.

The oxidation of ammonia to nitrate obviously needs a base since the organisms are very sensitive to acidity. Normally, this need is met by calcium carbonate, so that calcium goes into solution as nitrification proceeds. In absence of calcium

[1] R. M. Beesley, *Trans. Chem. Soc.*, 1914, **105**, 1014.
[2] *C.R.*, 1921, **172**, 173.
[3] *Biochem. J.*, 1934, **28**, 1575.
[4] *J. Bact.*, 1923, 8, 343.

carbonate, magnesium carbonate or mineral calcium phosphate also serve.[1]

II. Changes Suffered by the Nitrate: Losses of Nitrogen from Soil. Microbial Actions Causing Loss of Nitrogen: Denitrification.

The nitrate thus formed by certain groups of micro-organisms is liable to four kinds of loss: (1) assimilation by growing plants; (2) assimilation by micro-organisms; (3) decomposition by micro-organisms, and (4) leaching. The first of these has already been dealt with in Chapter II.: we shall now proceed to discuss the second and third. Even when the conditions exclude all possibility of leaching, the nitrate persists in the soil only so long as no easily decomposable organic matter is present. If sugar, starch, or fresh vegetable matter is added, the nitrate disappears rapidly. Part is assimilated by the organisms decomposing the organic matter thus helping to restore the original C/N ratio (p. 344). Part, however, is reduced. Many organisms in presence of easily oxidisable organic matter convert the nitrate to nitrite; some do this quantitatively, others only partially; some carry the reduction further and produce oxides of nitrogen,[2] gaseous nitrogen, or ammonia.

This process is called denitrification. It was one of the first microbiological changes to be studied.

Numerous organisms are able to carry it out, some of which can ferment or decompose organic compounds independently of their denitrifying action; others cannot. For the latter group, denitrification is anaerobic and there is some general relation between the amount of nitrate reduced and the quantity of organic compound oxidised: for

[1] Nitrification has been shown to go on in building stones, and to account for some of the weathering and disintegration. See J. J. Fox and T. W. Harrison, *J. Soc. Chem. Ind.*, 1925, **44**, 145T; T. and J. E. Marsh, *Stone Decay and its Prevention*, Blackwell, Oxford, 1926.

[2] See M. Beijerinck and D. C. J. Minkman, *Zbl. Bakt.*, Abt. II, 1910, **25**, 30.

the former group there is no relation at all,[1] and the action is not necessarily anaerobic. Another method of grouping used at Rothamsted cuts across this: J. Meiklejohn,[2] working with organisms picked off from the percolating filters at a sugar beet factory, found that of 80 strains of organisms examined under aerobic conditions, 13 failed to reduce nitrate and were poor fermenters; 29 also indifferent fermenters produced nitrite, but not in amount equal to the nitrate used; indeed for 9 the nitrite accounted only for 2 per cent. of this: 30 were all active fermenters, and quantitatively reduced the nitrate to nitrite; 8 carried the reduction to the stage of ammonia, which was usually equivalent to the nitrite first formed but not to the nitrate that had disappeared; 5 (including some of the above 30) produced nitrogen gas.

With so great a variety of possible actions it is not surprising that the mechanism of the reduction has not yet been elucidated. When nitrate was excluded from the medium and the conditions kept anaerobic the organism studied by Hulme[3] evolved gaseous hydrogen. This supports the old idea of Stoklasa and Mazé[4] that the reduction is due to nascent hydrogen. Korsakova, working with one of the groups that quantitatively reduce the nitrate to nitrogen gas, showed that there must be some intermediate product because for a period of the reaction the nitrate, nitrite, and nitrogen do not add up to the full amount: calculating the amount of the hypothetical intermediate by difference the curve of Fig. 41 is obtained. So far this substance has not been identified, though Blom[5] has adduced evidence that it is hydroxylamine.

[1] M. P. Korsakova in E. E. Uspensky, *Soil Microbiology in the U.S.S.R.*, Moscow, 1933.

[2] Jane Meiklejohn, *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 180.

[3] W. Hulme, *Trans. Chem. Soc.*, 1914, **105**, 623.

[4] Stoklasa and Vítek, *Zbl. Bakt.*, Abt. II, 1905, **14**, 102 and 183; P. Mazé, *Ann. Inst. Pasteur*, 1911, **25**, 289. But not all hydrogen-producing organisms can denitrify.

[5] *Biochem. Ztschr.*, 1928, **194**, 392. See also A. S. Corbet, *Biochem. J.*, 1934, **28**, 1575.

This aerobic denitrification apparently takes place in sewage beds and certain other effluent purification filters: it is difficult otherwise to account for the losses of nitrogen.

There is a very sharp contrast between the bacterial production and the bacterial destruction of nitrates. Active production of nitrate is confined at each stage to a few groups of organisms only, and the end result is a single product quantitatively equivalent to the original ammonia; no simple

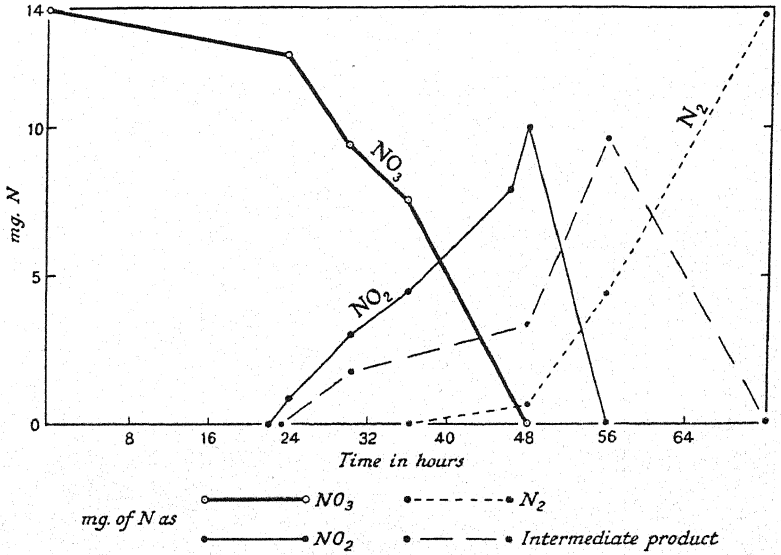


FIG. 41.—Bacterial reduction of nitrate. (M. P. Korsakova, quoted by E. E. Uspensky in *Soil Microbiology in the U.S.S.R.*). The hypothetical intermediate product accounts for the difference between the numbers of mg. of products obtained and 14 mg.

chemical process oxidises ammonia in this complete manner. The bacterial reduction of nitrates, on the other hand, gives a number of products not in any simple ratio, whilst the chemical reduction can readily be made to go quantitatively to ammonia.

The actions described above occur in culture media after inoculation with a little soil. Reduction of nitrate and loss of nitrogen also go on when the proportion of soil inoculum

is so increased that the volume of culture medium amounts only to the "saturation capacity" of the soil. They do not happen, however, to anything like so marked an extent when the proportion of liquid is further reduced so that it forms only 50 per cent. of the saturation capacity,[1] nor do they go on in absence of added supplies of easily decomposable organic matter and of nitrate.[2]

So far as is known evolution of gaseous nitrogen or its oxides occurs only from nitrates. No loss of nitrogen has been observed in the straightforward bacterial oxidation of organic substances such as albumin, asparagin, or mixtures such as urine or fæces.[3] Wherever losses have been recorded there has always been the possibility of nitrification as a first stage.

Loss of Nitrogen from the Soil.

The only one of the various changes discussed above involving the loss of nitrogen is the reduction to gaseous nitrogen or its oxides, and there is no clear evidence that this ever occurs in soils. The other changes, to nitrate, or ammonia, or assimilation by living organisms merely involves change of combination, not absolute loss.

Various experiments are, however, recorded which seem to suggest a loss of nitrogen from some cause, even where there is no leaching.

At the California Experiment Station, Burd and Martin [4] kept soils in large galvanised iron vessels for a period of eleven years, and compared the nitrogen contents at the end of the successive periods with those at the beginning. Some of the soils had been cropped and some kept fallow: they were

[1] O. Lemmermann and J. L. Wickers, *Zbl. Bakt.*, Abt. II, 1914, **41**, 608-625 (see graph, p. 624); A. Oelsner, *ibid.*, 1917, **48**, 210.

[2] V. Subrahmanyan, *J. Agric. Sci.*, 1927, **17**, 429 and 449; 1929, **19**, 627.

[3] Müntz and Lainé, *Ann. Inst. Nat. Agron.*, 1911, **10**, 5; Adeney (1908); E. J. Russell and E. H. Richards, *J. Agric. Sci.*, 1917, **8**, 495.

[4] J. S. Burd and J. C. Martin, *Hilgardia*, 1931, **5**, 455.

kept moist, but no drainage was allowed to take place. At the end of the first period the soils contained less nitrogen than at the beginning :—

	Cropped Land.	Uncropped.
Loss of nitrogen in grm. from 1600 lb. soil	198	—
In crops, grm.	65	—
Net loss, grm.	133	124

This corresponds to a loss of 100 lb. nitrogen per acre per annum from the top 9 inches of soil. In the second five-year period no further loss occurred, suggesting that it had been the result of the change of conditions from the field to the tank. If drainage had been completely excluded, and if there had been no interaction during the five years between the nitrate in the soil solution and the galvanised iron of the container, then one might assume a loss of gaseous nitrogen or a volatilisation of ammonia. Another instance is afforded by the pot experiments of J. A. Daji at Woburn.[1] Soil was mixed with green manures in normal proportions and cropped : there was a loss of nitrogen that was certainly not due to leaching. It was especially marked where there had been a temporary accumulation of ammonia, and this suggests that it may simply have been due to volatilisation of ammonia. The loss of nitrogen from water-logged soils dressed with organic manures is apparently due to this cause.[2]

Loss of Nitrogen where Leaching of Nitrate Occurs.

At Rothamsted a little plot of arable land, $\frac{1}{1000}$ acre in extent, has been kept free from vegetation by hoeing, but not otherwise disturbed, since 1870 ; by 1917 the top 9 inches had lost one-third of its original stock of nitrogen. The plot has been converted into a lysimeter by isolating it from the surrounding ground by cement partitions and then under-draining ; the drainage water is all collected and analysed.

[1] *J. Agric. Sci.*, 1934, **24**, 15.
[2] A. Sreenivasan and V. Subrahmanyan, *ibid.*, 1935, **25**, 6.

At the end of forty-seven years the amounts of nitrogen found as nitrate in the drainage waters were added up and found approximately to equal the total loss of nitrogen from the soil (Table 70). The experiment is not fine enough to justify any discussion of the small balance, but it shows that the loss of nitrogen is *mainly* due to leaching out of nitrates.

The obvious uncertainty attaching to so prolonged an experiment is reduced in this case by the fact that the determinations were for the last twenty-eight years of the period made by the same analyst. N. H. J. Miller found that the rate of loss of nitrogen per acre (estimated by the quantities of nitrates in the drainage water) was about 40 lb. per annum in the earlier years, and fell below 30 lb., and finally below 25 lb. per annum in the later years.

TABLE 70.—CHANGES IN NITROGEN CONTENT OF A SOIL KEPT FREE FROM VEGETATION FOR FORTY-SEVEN YEARS, BUT EXPOSED TO RAIN AND WEATHER. MILLER (1906), RUSSELL AND RICHARDS (1920).

Per Cent. of Nitrogen in Soil, top 9 inches.		Lb. of Nitrogen per Acre, top 9 inches.			Nitrogen Recovered as Nitrate, 1870–1917.
In 1870.	In 1917.	In 1870.	In 1917.	Loss in 35 years.	Lb. per Acre.[1]
·146	·099	3500	2376	1124	1247
	·097		2328	1172	1200

In field conditions where plants are growing in the soil the amount of drainage water is less than on the uncropped gauge, and the loss of nitrate is further reduced by any factor that improves plant growth. On the Broadbalk wheat field the autumn drainage water from plots receiving sulphate of ammonia contained on an average 18 parts of nitric nitrogen per million, while that on the plot receiving in addition potassic and phosphatic fertiliser contained only 8·5 parts per million.

[1] After deduction of the amount brought down in the rain. The upper line of figures refers to the 20-inch and the lower to the 60-inch gauge. Some nitrate is no doubt contributed by the sub-soil.

In the uncropped gauge experiment the conditions are simplified by the circumstance that there was no addition of vegetable matter to the soil, and consequently there was nothing in the nature of easily decomposable organic matter present. Growing plants, and particularly farmyard manure, add this kind of material, and therefore open up the possibility of reduction to gaseous nitrogen or oxides as described above. Certainly the losses in these circumstances are considerable. One of the Broadbalk wheat plots at Rothamsted receives annually 14 tons of farmyard manure per acre, supplying 200 lb. nitrogen. After allowing for the nitrogen taken up by the crop and left in the soil the deficit is enormous, amounting to nearly 70 per cent. of the added quantity. On the adjoining unmanured plot there is no deficit, the whole of the nitrogen lost from the soil being accounted for in the crop (Table 71).

TABLE 71.—LOSSES OF NITROGEN FROM CULTIVATED SOILS, BROADBALK WHEAT FIELD, ROTHAMSTED, 49 YEARS, 1865-1914.

Nitrogen Balance Sheet, 1865-1914. *Top 9 Inches. Lb. per Acre.*

	Farmyard Manure (Plot 2B).	No Manure (Plot 3).	Complete Artificials (86 lb. N).	
			(Plot 7.)	(Plot 13.)
N in soil in 1865, lb. per acre	4850	2960	3390	3320
per cent.	0·196	0·114	0·123	0·121
,, ,, 1914, lb. per acre	5590	2570	3210	3240
per cent.	0·236	0·092	0·120	0·122
Total change in 49 years, lb. per acre . .	+740	−390	−180	−80
N added in manure, seed and rain, per annum.	208	7	93	93
N removed in crops, per annum . . .	50	17	46	44
N retained (+) or lost (−) by soil per annum	+15	−8	−4	−2
N unaccounted for, per annum . . .	143	(gain 2)	51	51

Similar losses occur on the Woburn plots receiving farmyard manure annually.[1]

Unfortunately it is not possible to form any estimate of the amount of nitrate washed out by rain water, and so it is impossible to say whether leaching accounts for the whole of the loss or whether any volatilisation of ammonia or evolution of nitrogen gas takes place.

Similar losses occur when grassland is converted into arable land, or when virgin prairie soil is broken up for cropping. Oxidation and nitrification both proceed rapidly: part of the nitrate is taken up by the crop, but by far the greater part disappears and cannot be traced. It may be leached out, but the local observers usually consider this improbable. Shutt's analyses of the Indian Head soil, Saskatchewan, are given in Table 72. Here there is but

TABLE 72.—LOSSES OF NITROGEN CONSEQUENT ON BREAKING UP OF PRAIRIE LAND, TOP 8 INCHES. SHUTT (1910).

	Per Cent.	Lb. per Acre.
Nitrogen present in unbroken prairie	·371	6940
,, ,, after 22 years' cultivation	·254	4750
Loss from soil		2190
Recovered in crop		700
Deficit, being dead loss		1490
Annual dead loss		68

little drainage water, yet only one-third of the lost nitrogen is recovered in the crop. Snyder has given similar results for Minnesota [2] soils, and Swanson and Gainey for Kansas soils.[3]

The exhaustion of the soil is due, therefore, not to the removal of the crop, but to the cultivation (p. 346).

[1] *Fifty Years of Field Experiments at the Woburn Experimental Station*, E. J. Russell and J. A. Voelcker, with a Statistical Report by W. G. Cochran (Rothamsted Monographs, 1936).

[2] *Minn. Agric. Expt. Sta. Bull.* No. 53, 1897.

[3] C. O. Swanson, *Kansas Agric. Expt. Sta. Bull.* No. 199, 1914: see also No. 220, 1918; P. L. Gainey, M. C. Sewell, and W. L. Latshaw, *J. Amer. Soc. Agron.*, 1929, **21**, 1130; 1930, **22**, 639.

Gains of Nitrogen by the Soil. Nitrogen Fixation.

The losses of nitrogen recorded above do not continue indefinitely: a state of equilibrium is reached below which the nitrogen content of a natural soil does not fall so long as the conditions remain unchanged. Both at Rothamsted and at Woburn on the continuously unmanured wheat and barley plots the nitrogen content of the top 9 inches has fallen to 0·09 per cent. and it shows no signs of falling lower.

Moreover, if the soil is allowed to remain undisturbed and covered with permanent vegetation so that nitrates no longer accumulate but are readily taken up by the plants, then the content of nitrogen and of organic matter begins to rise. On the Broadbalk field a third plot adjacent to the two already mentioned was, in 1882, allowed to go out of cultivation and has not been touched since; it soon covered itself with vegetation, the leaves and stems of which enriched it in organic matter. The gain in nitrogen is very marked, as shown in Table 73. But it is in an organic form, and the nitrate and

Table 73.—Gains in Nitrogen in Soils Permanently Covered with Vegetation—Rothamsted Soils Left to Run Wild for 22-24 Years. Hall.[1]

	Broadbalk: $CaCO_3$, 3·32 per Cent.				Geescroft: $CaCO_3$, 0·16 per Cent.			
	Carbon, per Cent.		Nitrogen, per Cent.		Carbon, per Cent.		Nitrogen, per Cent.	
	1881.	1904.	1881.	1904.	1883.	1904.	1883.	1904.
1st 9 inches	1·14	1·23	·108	·145	1·11	1·49	·108	·131
2nd 9 inches	·62	·70	·070	·095	·60	·63	·074	·083
3rd 9 inches	·46	·55	·058	·084	·45	·44	·060	·065
Approximate gain in nitrogen,* lb. per acre . . .				2200				1400
Lb. per acre per annum . .				91·7				60

Land Laid Down to Grass in 1856 and Mown Annually (Dr. Gilbert's Meadow, Rothamsted).

	1856.[2]	1879.	1888.	1912.
Per cent. of N on top 9 inches .	[·152]	·205	·235	·338

[1] *J. Agric. Sci.*, 1905, 1, 241.

[2] Estimated.

ammonia both remain at low levels: the nitrate well below that of arable land, and the ammonia usually above it.[1] The gain in nitrogen is much influenced by the amount of calcium carbonate in the soil, and is considerably less on another plot in Geescroft field, where only little calcium carbonate is present; whether this is due to any specific action, or to the changed physical conditions brought out by decalcifying a soil, is not clear. Gains of nitrogen also take place on land covered with perennial grasses and clovers even when the crop is mown or grazed. On clay pastures dressings of basic slag, by improving the growth of herbage, have been found to increase the nitrogen content of the soil, whilst potassium salts, such as kainit, have had the same effect on sandy soil.

This effect of wild vegetation, sown grasses and clovers, in increasing the organic matter and nitrogen content of the soil has long been known to soil cultivators. The old method of replenishing soil fertility was to alternate the periods of arable cultivation with a year's "rest" when the soil was left to cover itself with wild or self-sown plants which were then ploughed under; this so-called fallow was prescribed one year in seven in the Mosaic law [2] and one year in three in mediæval England.[3] One of the greatest improvements in agriculture was the substitution of a definite sown crop of selected grasses and clovers for the indefinite mixture of self-sown plants of the mediæval fallow. In the Norfolk rotation introduced in the eighteenth century one year in four was given up to clover. In more recent rotations the clover or "seeds" mixture is sometimes left for two or three years before it is ploughed up, so that the enrichment may become more marked.

In humid climates the gains in nitrogen are greatest where

[1] In *Trans. 3rd Int. Soil Cong.*, Oxford, 1935, **1**, 220, H. L. Richardson has discussed the rate at which equilibrium is attained.

[2] *Leviticus* xxv. 1-7.

[3] T. Tusser, *Five Hundred Points of Good Husbandry*, 1573.

leguminous plants are most abundant, and the increase after a clover crop is so marked that it can be measured after one year only (p. 398).

The accumulation of nitrogen thus brought about does not go on indefinitely; in course of time a point of equilibrium is reached, higher or lower according to the soil conditions, where further gains are balanced by losses, so that the nitrogen content remains approximately constant.

III. Microbiological Activities Increasing the Amount of Nitrogen in Soils.

The Fixation of Nitrogen.

The first systematic search for a recuperative agency to make good the losses of nitrogen from the soil was started over fifty years ago by Berthelot (1885). He found that certain organic compounds could absorb free nitrogen under the influence of silent electric discharges, and at first attributed the natural recuperation to this cause. He also examined the possibility of bacterial action, as micro-organisms at that time were playing a large part in French science under Pasteur's influence. Accordingly he exposed sterilised and unsterilised sands and clays poor in nitrogen (0·01 per cent. or less) to air in large closed flasks for five months, and found distinct gains in nitrogen in the unsterilised, but not in the sterilised soils. Fixation was, therefore, not due to any external physical cause, which would operate equally in both cases, but to micro-organisms. There seems to have been an element of good fortune in this experiment, for when Gautier and Drouin [1] repeated it they obtained fixation of nitrogen only if sufficient organic matter was present in the soil. But the research was at once fruitful of results because it gave Hellriegel and Wilfarth the key to the clover problem (p. 391).

The possibility of nitrogen fixation by bacteria living independently of leguminous plants was put forward by

[1] *C.R.*, 1888, **106**, 754, 863 *et seq.*

P. Kossowitsch in 1894: [1] he showed that the alga *Nostoc* fixed nitrogen vigorously when associated with a crude culture of soil bacteria, and supplied with sugar; he attributed this to the bacteria, not to the alga. At that time it was not possible to prepare pure cultures of algæ so that he could not make the proof rigid: later workers have claimed that *Nostoc* can fix nitrogen even in the dark, provided it has a suitable source of energy such as glucose.[2] He regarded the combination, however, as a symbiosis like that of the nodule bacteria and the Leguminosæ. Bouilhac [3] developed the idea, and showed later that the mixture could act as a nitrogenous fertiliser: he obtained with it, for example, increased yields of buckwheat.

It was, however, Winogradsky (1895) who first isolated an organism capable of fixing gaseous nitrogen.

No investigator of our subject has shown greater ingenuity than Winogradsky in devising methods at once simple, direct, and effective. In looking for the nitrogen-fixing organisms he used his elective method which consists in making the conditions as favourable as possible for the group of organisms under investigation, and as unfavourable as possible for all others; he inoculated soil into a medium containing every nutrient except nitrogen compounds: only bacteria capable of assimilating gaseous nitrogen could therefore develop, and these had a clear field. But he further recognised that the process was endothermic and required some source of energy, hence he added sugar to the solution.

Winogradsky's solution contained 2 to 4 per cent. dextrose, a little freshly washed chalk, 0·1 per cent. K_2HPO_4, 0·05 per cent. of $MgSO_4$, and traces of NaCl, $FeSO_4$, and $MnSO_4$, together with a little soil. Under aerobic conditions nitrogen was assimilated and the sugar was decomposed with evolution of carbon dioxide and hydrogen and formation of *n*-butyric

[1] *Bot. Zeitg.*, 1894, **52**, 97.

[2] F. E. Allison and S. R. Hoover, *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 145.

[3] *C.R.*, 1896, **123**, 828; with Giustiniani, *ibid.*, 1903, **137**, 1274.

and acetic acids in the proportion of three or four molecules of the former to one molecule of the latter, the two acids together accounting for nearly half the sugar. A little alcohol was found, but practically no non-volatile acid. There was a distinct relationship between the amounts of nitrogen assimilated and of sugar decomposed, each milligram of nitrogen fixed requiring the oxidation of about 500 mgm. of sugar.

Three organisms were present, a Clostridium and two bacteria, which, however, could not be separated by the method of successive cultures. Not until recourse was had to anaerobic conditions were the two bacteria suppressed and the Clostridium obtained pure (1902). The bacteria having been isolated, it appeared that the Clostridium alone possessed the power of fixing nitrogen, but a fresh difficulty now arose because in pure cultures the organism acted only under anaerobic conditions. Only when the protective bacteria were simultaneously present did fixation go on in presence of air. The organism was called *Clostridium pasteurianum*: it formed rods 1·2 μ thick and 1·5 μ to 2 μ long and also spores.

In order to simplify the bacterial flora Winogradsky had heated his soil to 75° C., thereby killing non-spore formers, but Beijerinck (1901, 1902) discovered in untreated soil a group of three other nitrogen-fixing organisms: *Azotobacter chroococcum* (so called because it produces a dark brown pigment), *Granulobacter* and *Radiobacter*.[1] Of these, Azotobacter is the most active; in cultures it usually forms large cocci, or rods, 4 to 6 μ in thickness, but Löhnis and Smith [2] showed that it passes through a complex life cycle. It differs in three important respects from Clostridium: (1) it is aerobic; (2) it produces practically no butyric acid; (3) it fixes more nitrogen than Clostridium per grm. of sugar decomposed.

Other organisms have since been described as fixers of

[1] Later shown by Stoklasa and others (*Zbl. Bakt.*, Abt. II, 1908, **21**, 484 and 620) to possess only slight nitrogen-fixing power. For later studies see F. B. Smith and P. E. Brown, *Iowa St. Coll. J. Sci.*, 1935, **10**, 17.

[2] F. L. Löhnis and N. R. Smith, *J. Agric. Res.*, 1916, **6**, 675.

nitrogen,[1] but none is so effective as Azotobacter, and to this most of the investigations have been confined.

Several species of Azotobacter are known, including an interesting aquatic form, *Az. agilis*, found in Dutch canal waters.[2] The isolation of Azotobacter from soils has recently been greatly simplified by Winogradsky, using a silica jelly made up with calcium benzoate.[3] He and J. Ziemięcka have also developed a method for studying Azotobacter in the soil and so discovering its relations in natural conditions.[4] A third method, the manometric method of O. Warburg, has been used with good results by Dean Burk for the study in culture solutions of the gaseous phase of the reaction, the relations between respiration, growth, and nitrogen fixation.[5]

These various methods have brought out the importance of certain factors in the reaction. A small quantity of soil added to the culture medium has long been known to facilitate the development of Azotobacter. In a classical investigation, Krzemieniewski [6] showed that pure cultures fail to retain their effectiveness unless a little soil is present. The active agent is the humus, but its effect is not to furnish carbon or nitrogen to the organism, and it loses its power after treatment with hydrochloric acid. Remy and Rösing,[7] and Carsten Olsen,[8] attributed the action to the iron invariably present. This has been abundantly confirmed by the newer methods, but it

[1] *E.g. Amylobacter:* see G. Bredemann, *Zbl. Bakt.*, Abt. II, 1909, **23**, 385.

[2] A. J. Kluyver and H. van Reenen, *Arch. Mikrobiol.*, 1933, 4, 280: also observed by Hugh Nicol in a Norfolk ditch.

[3] S. Winogradsky, *Soil Sci.*, 1935, **40**, 59. On the average 11 mg. N is fixed per grm. of benzoic ions.

[4] *Ann. Inst. Pasteur*, 1928, **42**, 36; also J. Ziemięcka, *J. Agric. Sci.*, 1932, **22**, 797.

[5] Dean Burk, *J. Phys. Chem.*, 1930, **34**, 1174; *Soil Sci.*, 1932, **33**, 413 and 455 (with H. Lineweaver and C. K. Horner); *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 148 (with C. K. Horner).

[6] *Bull. Acad. Sci.*, Cracovie, 1908, 931.

[7] Th. Remy and G. Rösing, *Zbl. Bakt.*, Abt. II, 1911, **30**, 349.

[8] Carsten Olsen, *C.R. Carlsberg*, 1930, **18**, 1. See also K. Bassalik and J. Neugebauer, *Acta Soc. Bot. Polon.*, 1931, **8**, 213, and 1933, **10**, 481.

is also shown that minute traces of vanadium and of molybdenum markedly increase the growth of Azotobacter.[1] Calcium compounds also play an important part in the process. The effect of nitrogen compounds is very marked. Addition of small quantities to culture media is beneficial in the early stages, particularly for growth of the organisms, also, though to a less extent, for nitrogen fixation.[2] Larger quantities of nitrate are favourable for growth, but beyond a certain point suppress nitrogen fixation altogether,[3] the organism apparently assimilating nitrate in preference to free nitrogen.

In soil, however, nitrogenous manures appear to be positively harmful to Azotobacter as shown by the following relative numbers on the Broadbalk plots :—[4]

	No Manure since 1839.	Phosphate and Potash only, no Nitrogen.	Phosphate and Potash and Nitrate of Soda or Sulphate of Ammonia.		Farmyard Manure, 200 lb. N per Acre.
			43 lb. Nitrogen per Acre.	86 lb. Nitrogen per Acre.	
Phosphate added to "plaque" .	30	30-40	10-20	0	20
No phosphate added . .	0	30-40	10-20	0	20

The strains of Azotobacter occurring in temperate climates are more sensitive to acidity than is Clostridium: indeed Ashby[5] found that the relative distribution of Azotobacter and Clostridium at Rothamsted depended on the amount of calcium carbonate in the soil; wherever any notable quantity was present, Azotobacter invariably occurred: otherwise Clostridium alone was found. This result appears to be

[1] Bortels, *Arch. Mikrobiol.*, 1930, **1**, 330. See Dean Burk and C. K. Horner, *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 152, for a discussion of the observations.

[2] T. L. Hills, *J. Agric. Res.*, 1918, **12**, 183.

[3] A. Bonazzi, *J. Bact.*, 1921, **6**, 331.

[4] J. Ziemięcka, *J. Agric. Sci.*, 1932, **22**, 797.

[5] *J. Agric. Sci.*, 1907, **2**, 35.

general.[1] Gainey showed that Azotobacter occurs in soil with a *p*H value 6·0 or more, but not in those with *p*H value 5·9 or less.[2] This sensitiveness on the part of Azotobacter has been used as a means of assessing the lime requirements of soils (p. 475). Other strains of Azotobacter, very tolerant of acidity, have been found in Malayan soil.[3]

On the other hand, Azotobacter is very tolerant of salts of the alkalis and generally of the conditions of alkali soils.

The nitrogen-fixing power of Azotobacter is greatly increased by the presence of other organisms, whether bacteria, algæ, or protozoa. Beijerinck and van Delden (1902) and J. G. Lipman [4] recognised that mixed cultures fixed more nitrogen than pure cultures, while Hanzawa showed that two species of Azotobacter growing together fixed more nitrogen than either separately.[5] Omeliansky and Solounskov [6] explained the increased fixation brought about by a mixture of Clostridium and Azotobacter by supposing that Azotobacter, being vigorously aerobic, maintained local anaerobic conditions for the Clostridium, so that both were able to work. C. B. Lipman and L. J. H. Teakle [7] supposed that the alga *Chlorella* increased fixation by providing necessary carbon compounds.

D. M. Novogrudsky [8] studied the stimulating effect of *Bac. Stutzeri* and *Bac. denitrofluorescens*.

[1] Hugo Fischer (*J. Landwirt.*, 1905, **53**, 61) found Azotobacter on the limed plots at Bonn-Poppelsdorf, but not on the unlimed. Burri found it in only one-third of the Swiss soils examined. W. Brenner rarely found Azotobacter in the soils of Finland; these are normally very acid (*Suomen Geol. Kom., Agrogeol. Julkaisuja*, No. 20, 1924).

[2] *J. Agric. Res.*, 1918, **14**, 265. E. B. Fred and A. Davenport found the limits in culture solutions to lie between 6·5 and 8·6 (*J. Agric. Res.*, 1918, **14**, 317).

[3] R. A. Altson, *J. Agric. Sci.*, 1936, **26**, 268.

[4] *New Jersey Expt. Sta., 24th Ann. Rept.*, 1903, p. 217.

[5] *Zbl. Bakt.*, Abt. II, 1914, **41**, 573. On the other hand, Mahmoud Selim found that a mixture of two strains fixed no more nitrogen than either singly (*Proc. 2nd Int. Cong. Soil Sci.*, Moscow, 1930, **3**, 82).

[6] *Zbl. Bakt.*, Abt. II, 1919, **49**, 473 (abstract only).

[7] *J. Gen. Physiol.*, 1925, **7**, 509.

[8] *Trans. Inst. Fertilisers*, No. 76, 1930, 69, Moscow.

Cutler attributes the effect of protozoa [1] to three actions :—

(1) Increased individual efficiency resulting from the smaller size of the population.

(2) The removal by the protozoa of the older cells of Azotobacter leaving the field clear for the younger and more vigorously growing organisms which are probably the most active fixers of nitrogen.[2]

(3) The removal of the nitrogen fixed by Azotobacter by transferring it from their bodies (in which it chiefly occurs) to the bodies of amœbæ feeding upon them in which form it can accumulate without hampering the fixation process.

Little is known of the chemistry of the fixation. Azotobacter completely oxidises the sugar or other carbon compound to CO_2 and water, the volume of CO_2 being equal to that of oxygen absorbed.[3] In contradistinction to *Clostridium* (p. 383) Azotobacter produces no acid or alcohol.

The reaction by which the nitrogen is fixed is not yet known. Ammonia is found in the culture solution, and is regarded by Winogradsky [4] as the first stage in the process. Dean Burk and C. K. Horner,[5] on the other hand, consider that the ammonia is more probably a degradation product since Azotobacter has considerable power of forming ammonia from complex organic compounds. Dean Burk argues that some enzyme is involved,[6] but nothing definite is known.

There is some connection, though not a close one, between the amount of nitrogen fixed and the chemical nature of the compound supplied. Sugars are on the whole the most efficient nutrients; the older workers usually obtained

[1] S. M. Nasir, *Ann. Appl. Biol.*, 1923, **10**, 122; D. W. Cutler and D. V. Bal, *ibid.*, 1926, **13**, 516.

[2] A. Koch and S. Seydel, *Zbl. Bakt.*, Abt. II, 1912, **31**, 570.

[3] The oxidation is so vigorous in culture solution that 1 grm. weight has evolved no less than 1·3 grm. CO_2 in twenty-four hours (Stoklasa and Ernest, 1905).

[4] He discusses the question in *Soil Sci.*, 1935, **40**, 59.

[5] *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 148. See also E. E. Uspensky, *Soil Microbiology in the U.S.S.R.*, 1917-1932, Moscow, 1933.

[6] *Ergebnisse der Enzymforschung* (*Nord und Weigenhagen*), 1934, **3**, 23.

a fixation of 7 to 10 mg. of nitrogen per gram of sugar decomposed.[1] Gainey, however, shows that the different strains of Azotobacter vary greatly in their activity, and that no general order of effectiveness of organic compounds can be assigned.[2]

It has generally been assumed that the process of converting gaseous nitrogen into protein is necessarily exothermic, and that a certain amount of energy is needed to bring it about: the need for easily decomposable organic matter is thus explained. The process would strike an engineer as very inefficient, since only about 1 per cent. of the energy consumed is utilised in nitrogen fixation.[3] Dean Burk,[4] however, shows that an endothermic reaction is possible which would allow the whole process to go on without the necessity for any energy from the oxidation of organic matter.

It is difficult to obtain clear evidence showing how much nitrogen is fixed in soils in natural conditions by free-living nitrogen-fixing organisms. Wherever a gain in nitrogen has been recorded in natural conditions in humid climates, there have also been leguminous plants growing to which it might be attributed.

In laboratory experiments, however, soils free from leguminous vegetation have gained in nitrogen when all the conditions necessary for the action of Azotobacter are satisfied. Usually sugar or other non-nitrogenous organic matter is added to the soil, and the changes in nitrogen content studied. The sugar has the double effect of removing nitrate from the soil (p. 353) and of supplying energy for the organism, both

[1] F. Löhnis and N. K. Pillai; Gerlach and Vogel, *Mitt. K. Wilhelm Inst.*, Bromberg, 1902, **9**, 817, and 1903, **10**, 636. For other compounds see H. S. Reed and B. Williams, *Zbl. Bakt.*, Abt. II, 1915, **43**, 166.

[2] P. L. Gainey, *Ann. Missouri Bot. Gard.*, 1928, **15**, 113-168.

[3] G. A. Linhart, *J. Gen. Physiol.*, 1920, **2**, 247.

[4] *J. Gen. Physiol.*, 1927, **10**, 559. This subject of the energy of fixation is fully discussed by P. W. Wilson and W. H. Peterson in "The Energetics of Heterotrophic Bacteria," *Chemical Reviews*, 1931, **8**, 427.

of which are essential to its activity. Generally there is a gain of nitrogen.[1] A. Koch *et al.* (1907) added successive small doses of dextrose to 500 grm. of loam, mixed with sand and spread on plates to secure copious aeration, kept uniformly moist and at 20° C. For each gram of dextrose supplied in the small doses, about 8 mg. of nitrogen were fixed during the first eight weeks; but only 4 or 5 mg. later on. In larger doses the sugar was less effective.

Pot experiments showed that the nitrogen thus added to the soil became available for plant food. Dextrose and sucrose first depressed the crop, then caused an increase, and finally left the soil richer in nitrogen at the end of the experiment than at the beginning [2] (Table 74).

TABLE 74.—EFFECT OF DEXTROSE AND SUCROSE ON THE PRODUCTIVENESS AND NITROGEN CONTENT OF THE SOIL. KOCH *et al.* (1907).

Sugar added per 100 grm. of Soil.	Crops Obtained.				Total N Removed in both Crops.	Nitrogen Left in Soil, Spring, 1906.	
	Oats, 1905.		Sugar Beets, 1906.				
	Dry Matter.	Yield of N.	Dry Matter.	Yield of N.	Grm.	Total N per Cent.	N as Nitrate, Parts per Million.
None . .	100	100	100	100	0·5914	·093	10
2 grm. dextrose .	32·8	62·5	186	190	0·6814	·105	17
2 grm. cane sugar .	33·3	58·7	179	195	0·680	·105	15
4 grm. cane sugar .	37·7	78·1	283	339	1·0992	·119	37

When the soil temperature fell too, low nitrogen fixation ceased: it was not observed at 7° C. although it appeared to go on at 15°. For strains found in temperate climates the optimum temperature lay between 25° and 30° C.

[1] *E.g.* Ph. Schneider, *Landw. Jahrb.*, 1906, **35**, Ergänz. Bd. IV, 63.

[2] O. Lemmermann and R. Themlitz (*Ztschr. Pflanz. Düng.*, 1934, B, **13**, 353) also found that addition of sugar to soil slightly raised its nitrogen content.

On the other hand, F. Löhnis showed that the mixed cultures of the soil are almost as effective at 10° as at 20° C.[1]

10°-12° C.	20°-22° C.	30°-32° C.
3·15 mg.	4·55 mg.	4·27 mg. nitrogen fixed.

Field trials made at Rothamsted showed crop increases for autumn applications of sugar but decreases for spring dressings.[2]

Increased yields of sugar cane have followed the application of molasses to soil at the Station Agronomique and on W. P. Ebbels' estate in Mauritius [3] where the residual effect was well shown, and also in Antigua.[4] Of course it does not follow that the sugar has caused any fixation of nitrogen, and in point of fact H. A. Tempany and F. Giraud,[5] recognising that the soils were already rich in nitrogen and organic matter, attributed the effect to a partial sterilisation by the molasses, an initial removal of nitrate and a subsequent enhanced nitrification at a time when the sugar cane most needed it.

In Hawaii, on the other hand, Peck obtained no increases in yield from molasses but only marked losses of nitrate,[6] as also did Harrison in British Guiana.[7] Pfeiffer and Blanck [8] also failed to obtain any beneficial results by adding sugar to field soils. The subject is attracting attention in India, where the fertilising action has been confirmed, and attributed in part at any rate to fixation of nitrogen.[9]

[1] *Mitt. Landw. Inst.*, Leipzig, 1905, **7**, 94.

[2] H. B. Hutchinson, *J. Agric. Sci.*, 1918, **9**, 92.

[3] See *The Agricultural News*, 1908, **7**, 127; 1910, **9**, 339; and 1911, **10**, 179.

[4] *West Indian Dept. Agric.*, Pamphlet Ser. No. 64, 1910, No. 68, 1911.

[5] "The Application of Molasses as a Fertilizer," *Mauritius Dept. Agric. Bull.* 28, 1923.

[6] *Hawaii Sugar Planters Expt. Sta.*, Agric. Chem. Ser., Bulls. **34**, 1910, **37**, 1911, **39**, 1912. These provsde an interesting discussion on the losses of nitrogen from soil.

[7] *West India Bull.*, 1913, **13**, 126.

[8] *Landw. Vers.-Sta.*, 1912, **78**, 375.

[9] Dhar and Mukerji, *Proc. Acad. Sci. U.P.*, 1934, **4**, 175, 330; 1935, **5**, 61. The sugar rapidly decomposes in the soil Bhaskaran and Subrahmanyan suggests that its decomposition products, the fatty acids, would be more economical (*Proc. Indian Inst. Sci.*, 1936, B, **3**, 143).

Certain compounds producible in the decomposition of cellulose also serve as energy material for nitrogen fixation by Azotobacter [1] and Clostridium [2] as also do animal fæces, but their value depends on the diet of the animal.[3]

Leaves, stubble, etc., added to soil can increase nitrogen fixation, though under other conditions they can, like sugar, depress the nitrate content of the soil.[4]

In arid climates the evidence for activity of Azotobacter in the soil seems stronger. The continued cultivation of wheat may be followed by a slight increase rather than a decrease in the nitrogen content of the soil (p. 404). The heads are stripped off with the header and most of the straw is ploughed in ; nitrogen fixation apparently proceeds actively, the temperature conditions being suitable.[5]

Nitrogen Fixation by Bacteria in Symbiosis with Leguminosæ.

In humid climates there is no question that leguminous crops provide the chief supply of nitrogen in soil. After Hellriegel and Wilfarth's great discovery of the relationship between bacteria and leguminosæ (p. 25), many unsuccessful attempts were made to isolate and study the organisms by the methods then in vogue. Beijerinck (1888) broke away from the ordinary meat-bouillon-gelatine plate and substituted a slightly acid medium made up of infusion of pea leaves, gelatine (7 per cent.), asparagine (0·25 per cent.), and sucrose (0·5 per cent.). Growth readily took place, and the colonies yielded rods 1 μ wide and 4 to 5 μ long, some of which

[1] I. G. McBeth, *U.S.D.A., Bur. Plant. Ind., Circ.* No. 131, 1913. McBeth employed three kinds of bacteria (used separately in association with Azotobacter) to decompose the cellulose *in situ*. For other references see W. Bucksteeg, *Zbl. Bakt.*, Abt. II, 1936, **95**, 1.

[2] H. Pringsheim, *Biol. Cbl.*, 1911, **31**, 65.

[3] E. H. Richards, *J. Agric. Sci.*, 1917, **8**, 299.

[4] J. Dvořák, *Zischr. Landw. Versuchs. Österreich.*, 1912, **15**, 1077 ; H. B. Hutchinson, *J. Agric. Sci.*, 1918, **9**, 92.

[5] J. E. Greaves, *Zbl. Bakt.*, Abt. II, 1914, **41**, 444.

showed signs of bacteroid formation, and "swarmers" 0·9 μ long and 0·18 μ wide, these being among the smallest soil organisms known.[1]

The organisms pass through a definite life cycle. This was worked out by W. F. Bewley and H. B. Hutchinson [2] for culture solutions. A series of changes occur both in the nodule [3] and in the soil, but it is not known whether these are truly cyclic.

Beginning with the non-motile cocci: these swell, develop flagella, and become motile (the "swarmers" of the older

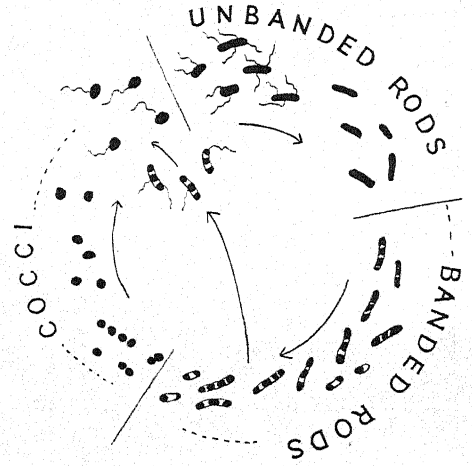


FIG. 42.—A life cycle of *Bacillus radicicola* in normal beneficial form.

workers); next they elongate and develop more flagella, becoming motile rods; finally they lose their flagella, become non-motile and vacuolated, taking on a banded appearance; they may be straight or branched. These then break up, releasing the cocci and so the cycle starts again (Fig. 42).

The branched T or Y forms are the bacteroids commonly

[1] J. Golding has shown that they will even pass through a porcelain filter, and has prepared pure cultures in this way.

[2] *J. Agric. Sci.*, 1920, **10**, 144.

[3] I. E. Wallin, *J. Bact.*, 1922, **7**, 471.

seen in the nodule; their formation in culture media is stimulated by sugars or small quantities of organic acids such as occur in the sap of the host plant.[1] On the other hand, H. G. Thornton and N. Gangulee [2] showed that the formation of the cocci, which quickly become the motile swarmers, is much stimulated by addition of phosphates or of milk; as many as 80 per cent. of the organisms in a culture can be brought into this form.

Unlike most other soil organisms, *Bacillus radicicola* does not occur in all regions; it is found only in places where its host plants live, thus having the unusual property of a discontinuous geographical distribution. But although apparently tied to its host plants, it is not confined to the nodule, but occurs independently in soil where it can live for ten or more years without its host plant;[3] it has, indeed, been isolated from soil by various workers.[4] It has even been supposed to fix nitrogen during this independent existence, but the evidence is not very good.[5]

Nothing was known of the life of the organism in the soil till Thornton and Gangulee (p. 395) ingeniously overcame the difficulties of the investigation. Using a modification of Winogradsky's 1905 direct staining method they were able to show that the organism goes through the same cycle in the soil as in culture solution, and that the development of motility is stimulated by addition of phosphates. Under favourable conditions of moisture, temperature, and soil packing the motile forms can travel through the soil at the rate of 1 inch in twenty-four hours; in normal conditions the rate is probably slower. The older estimates of 1 inch in forty-eight to seventy-two hours may not be far out,[6] while in

[1] A. Stutzer, *Zbl. Bakt.*, Abt. II, 1901, **7**, 897.

[2] *Proc. Roy. Soc.*, 1926, B, **99**, 427.

[3] A. L. Whiting, *J. Amer. Soc. Agron.*, 1925, **17**, 474.

[4] See C. B. Lipman and L. W. Fowler, *Science*, 1915, **41**, 256 and 725, for the methods used.

[5] See Marie P. Löhnis, *Soil Sci.*, 1930, **29**, 37.

[6] K. F. Kellerman and E. H. Fawcett, *Science*, N.S., 1907, **25**, 806.

drier or more compact conditions spreading may be exceedingly slow.[1]

Multiplication occurs at two stages in the cycle but in different ways; the motile rods divide by binary fission and the banded rods by multiple fission, this being the more important. In consequence of these differences, the total number of organisms in a soil does not remain constant, even under constant external conditions such as temperature, moisture supply, etc.; it continually varies (Fig. 43).

The mode of entry of the organisms into the plant was first studied by Marshall Ward (1887), later by Nobbe and Hiltner (1893-1896), and more recently by Fred at Wisconsin and Thornton at Rothamsted.

Nodules seldom appear until after the first true leaf is expanded.[2] At about this time the plant secretes from its roots some substance which stimulates multiplication of the bacteria around it. Near the tip of the root hair a small colony of the bacteria forms and produces a thermostable substance,[3] which causes the root hair to grow asymmetrically and become curled at the end, and in this curled region the bacteria enter. This deformation appears to depend upon a suitable ratio of available carbohydrate to nitrogen in the hair; it is inhibited by nitrates and by ammonium sulphate, but the inhibition is counteracted by dextrose.[4] The method of penetrating the deformed cell wall is not known.

The organisms are remarkably specific in their host plants. Some fifteen to twenty varieties are so far known, each of which can infect only a limited number of species.[5] This specificity is of great agricultural importance, and explains the necessity for supplying the appropriate bacteria where certain

[1] See W. C. Frazier and E. B. Fred, *Soil Sci.*, 1922, **14**, 29.

[2] H. G. Thornton, *Proc. Roy. Soc.*, 1929, B, **104**, 481.

[3] This can be separated from the bacteria by filtration. H. G. Thornton and Hugh Nicol, *Nature*, 1936, **137**, 494.

[4] H. G. Thornton, *Proc. Roy. Soc.*, 1936, B, **119**, 474.

[5] E. B. Fred, I. L. Baldwin, and E. McCoy, *Root Nodule Bacteria and Leguminous Plants*—Madison (University of Wisconsin Publication, 1932).

leguminous crops are being introduced into a new district. One method is to dress the land with soil from a field where the crop has recently grown successfully. The other is to

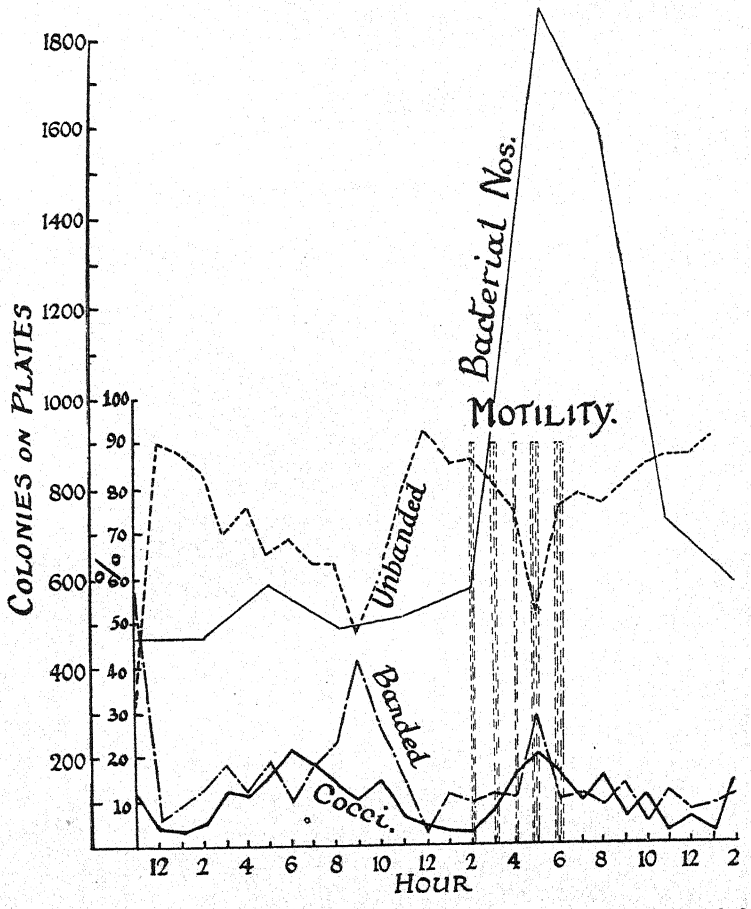


FIG. 43.—Total number of organisms, and percentages as cocci, banded and unbanded rods, at two-hourly intervals in a culture.[1]

grow the bacteria in pure culture and introduce them along with the seed; this method was introduced by Hiltner (1900-1903) with variable success, and it has been greatly improved

[1] H. G. Thornton and N. Gangulee, *Proc. Roy. Soc.*, 1926, B, **99**, 427.

by Chr. Barthel in Sweden,[1] H. Christensen in Denmark, Harrison and Barlow in Canada (1907), Thornton in England (1929), and others.

The reason for the specificity of the host plant is not known. Various of the organisms can cause the root hairs to curl,[2] but only the specific organisms can enter. The exclusion of "foreign" nodule bacteria may be a protein reaction, since serological tests place both the nodule bacteria and the proteins of the seeds of the host plants into their inoculation groups.[3]

The bacteria pass down the root hairs as a zoogloeal thread called the "infection thread." They enter the cortical cells of the root in several ways,[4] but usually by ramification of the "infection thread" through the host cells. The cellulose layers of the cell walls become perforated, thereby affording a way in for the infection thread.[5] Within the cells the thread becomes encased in a sheath of cell-wall material, and when this is ruptured the bacteria pass into the cytoplasm of the host cells where they multiply rapidly.[6]

Cell division in the cortical tissues is stimulated by the presence of the bacteria, and the young nodule develops. The history of the host cell after infection varies according to the plant. In many plants the cell ceases to divide, and the region of division then becomes limited to the newly formed cells in the outer distal region of the nodule, not yet reached by the bacteria.

In lupins the host cells continue to divide after infection, and the bacteria are carried along with the chromosomes into the new cells. In beans the bacteria spread principally in the inter-cellular spaces, but it is not clear how the bacteria penetrate into the cells.

[1] *Medd. Kgl. Vet. Akad. Nobelinst.*, Stockholm, 1919, **5**.

[2] Fred, Baldwin, and McCoy, *Root Nodule Bacteria*, 1932, p. 136.

[3] I. L. Baldwin, E. B. Fred, and E. G. Hastings, *Bot. Gaz.*, 1927, **83**, 217.

[4] P. F. Milovidov, *Zbl. Bakt.*, Abt. II, 1926, **68**, 333.

[5] E. McCoy, *Proc. Roy. Soc.*, 1932, B, **110**, 514.

[6] H. G. Thornton, *Ann. Bot.*, 1930, **44**, 385.

As the nodule develops vascular strands grow out along its sides from the root and supply the bacteria with carbohydrates.

In all types of nodule, the bacteria multiply within the cytoplasm of the host cells filling them completely, and developing swollen or branched forms probably as the result of some constituent of the plant cell. As these are by far the greater proportion of the bacteria they are probably the agents bringing about the nitrogen fixation.

A delicate equilibrium exists between the host plants and their bacteria. Active symbiosis resulting in nitrogen fixation seem to depend upon an adequate supply of available carbohydrate to the bacteria; if nodule-bearing lucerne plants are kept in the dark so as to arrest photosynthesis, the bacteria become actively parasitic on the nodule tissues.[1] *Vicia faba*, grown in a boron-deficient solution, fails to develop the vascular strands and so supplies no carbohydrate to the bacteria; here again they become parasitic.[2] This change to parasitism apparently occurs normally in old lucerne and clover nodules.[3]

When the bacteria become parasitic the nodule meristem ceases to grow.

Strains of the organisms differ both in their capacity to produce nodules and in the activity of the nodules; some strains even fail to increase the nitrogen in the plant.[4] It is not known whether these inefficient strains occur frequently, but they may have considerable practical importance, and some at any rate compete actively with beneficial strains and prevent the latter from developing nodules.[5]

Strains may be beneficial on one host plant and relatively inefficient upon another plant upon which they can yet

[1] H. G. Thornton, *Proc. Roy. Soc.*, 1930, B, **106**, 110.

[2] W. E. Brenchley and H. G. Thornton, *ibid.*, 1925, B, **98**, 373.

[3] H. G. Thornton, *ibid.*, 1930, B, **106**, 110.

[4] Fred, Baldwin, and McCoy (*Root Nodule Bacteria*, 1932, pp. 136, 170, 171) record relations between efficiency and certain serological tests.

[5] D. H. Dunham and I. L. Baldwin, *Soil Sci.*, 1931, **32**, 235.

produce nodules.[1] The efficiency can be altered after repeated passage through the host plant.[2]

Phosphates, calcium [3] and manganese compounds,[4] and other substances stimulate nodule formation.

The mechanism of nitrogen fixation is not understood. Active nodules contain measurable amounts of amino-nitrogen, but neither ammonia nor nitrates, unless these are supplied to the plant from outside. The Winogradskys [5] suppose the chemical changes involved in the fixation to be similar to those for Azotobacter, ammonia being the first product. Blom,[6] however, regards hydroxylamine as the first stage. Virtanen and Laine [7] discuss reactions that could give rise to aspartic acid, which in their view play an important part in the process.

The amount of nitrogen fixed is so large that it is easily measured in the field. When the host plant dies, or is ploughed into the ground, the nitrogen compounds speedily change into nitrates. A uniform piece of ground at Rothamsted was divided in 1873 into two parts; on one clover was grown, on the other barley. After removing the crops in 1874 barley was grown in both plots. The analytical results are given in Table 75.

[1] G. E. Helz, I. L. Baldwin, and E. B. Fred, *J. Agric. Res.*, 1927, **35**, 1039.

[2] O. N. Allen and I. L. Baldwin, *Wisc. Agric. Expt. Sta. Res. Bull.* No. 106, 1931.

[3] J. K. Wilson, *Cornell Agric. Expt. Sta. Bull.* No. 386, 1917. W. A. Albrecht and G. M. Horner, *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 140. Farmyard manure and straw exert a beneficial effect on the clover crop (E. J. Russell, *J. Bd. Agric.*, 1919, **26**, 124). H. G. Thornton, *J. Agric. Sci.*, 1929, **19**, 563, and on lucerne, F. J. Sievers and H. F. Holtz, *Wash. Agric. Expt. Sta. Bull.* No. 206, 1926.

[4] D. A. Olaru, *C.R.*, 1915, **160**, 280. Also, *Le Rôle du manganèse en agriculture*, Paris, *Baillière et fils*, 1920.

[5] S. Winogradsky (with H. Winogradsky), *Ann. Inst. Pasteur*, 1936, **56**, 221.

[6] *Zbl. Bakt.*, Abt. II, 1931, **84**, 60: see also Endres, *Liebig's Ann.*, 1935, **518**, 109.

[7] A. I. Virtanen and T. Laine, *Suomen Kemistilehti*, 1936, **9**, 5 and 12.

TABLE 75.—INFLUENCE OF CLOVER ON NITROGEN CONTENT OF SOIL.

	Plot where Clover was Grown.	Plot where no Clover was Grown.
Nitrogen in crop (1873), lb. per acre	151·3 (in clover)	37·3 (in barley)
Nitrogen left in soil after crop was removed (1873), per cent.	0·157	0·1
Nitrogen in crop (1874), lb. per acre	69·4 (in barley)	39·1 (in barley)

In sand cultures some of the nitrogen compounds, chiefly aspartic acid and lysine, pass out from the root of the leguminous plant and can be taken up by a non-leguminous crop growing alongside of it,[1] but whether this occurs in the soil is not clear.[2]

Demolon and Dunez[3] have found in old lucerne leys a bacteriophage that can dissolve the nodule bacteria of the lucerne plant. They explain in this way the failure of lucerne to persist on the same land for more than a few years: the "lucerne sickness" of the practical man.

Effect of Green Manuring.

The striking results recorded in Table 75 illustrate a fact well known to agriculturists, and much used in farm practice, that green crops ploughed into the soil under certain circumstances enrich it. The method is called green manuring: tares, mustard, or other crops are sown, and when fully grown are ploughed-in.

The effects depend on the composition of the crop and on the time of ploughing-in. In the classical Woburn experiments tares and mustard have been grown and ploughed-in every second year from 1892 to the present time. They not

[1] A. I. Virtanen, *Chem. and Ind.*, 1935, **54**, 1015 (with S. von Hausen and others; see p. 559).

[2] R. A. Greene (*Soil Sci.*, 1935, **39**, 327) finds that Azotobacter *spp.* also produce appreciable quantities of these and other amino-acids.

[3] A. Demolon and A. Dunez, *C.R.*, 1933, **197**, 1344; 1934, **199**, 1257; *Ann. Agron.*, 1935, **5**, 89.

only failed to increase the nitrogen content of the soil but did not even prevent its impoverishment. The nitrogen contents of the soils were :—[1]

	Averages Continuous Wheat and Barley. Stackyard Field.			Green Manure and Wheat in alternate Years since 1892. Lansome Field.	
	No Manure or Minerals only.	Artificial Manure, Sulphate of Ammonia or Nitrate of Soda.	Farmyard Manure.	Tares.	Mustard.
At beginning of experiment, 1876 (about) .	0·155	0·155	0·155	—	—
In 1932 . .	0·108	0·099	0·124	0·084	0·073

In the experiments of T. L. Lyon and B. D. Wilson [2] the ploughing-in of crops grown only during autumn failed to balance the losses following on a summer fallow, so that the net result was a loss of nitrogen. This was greatest for buckwheat and oats, and least for vetches and rye : it was greater as the plants became more mature (*i.e.* richer in carbon).

Land under grass which was not disturbed for summer fallow, however, continued to gain nitrogen.

Transformation of Organic Sulphur Compounds in the Soil.[3]

Sulphur is a normal constituent of many plant proteins where it occurs as cystine and cysteine. When the proteins are decomposed by bacteria the sulphur appears as hydrogen

[1] E. M. Crowther, in *Fifty Years of Field Experiments at the Woburn Experimental Station*, E. J. Russell and J. A. Voelcker (Rothamsted Monographs, 1936).

[2] *Cornell Agric. Expt. Sta.*, Mem. 115, 1928.

[3] An admirable review by H. J. Bunker of the physiology and biochemistry of the sulphur bacteria has been published by the *Dept. Sci. Ind. Res.*, Special Rept. 3, 1936, price 9d. This should be consulted for further details.

sulphide, occasionally as mercaptan.[1] Hydrogen sulphide is then attacked by the sulphur bacteria: oxidised first to sulphur, then to sulphate, in which form it is taken up by plants and built into the protein molecule; it then passes once more through its cycle of changes. Under certain anaerobic conditions, the sulphate, instead of being taken up by plants, is reduced to sulphide, and sulphur also can be reduced to hydrogen sulphide.

The oxidising bacteria are autotrophic, obtaining carbon from the CO_2 of the air and energy from the oxidation of inorganic substances. They fall into three groups which respectively oxidise:—

(1) H_2S to sulphur which is deposited within the cells;
(2) H_2S and also thiosulphates and tetrathionates, frequently depositing sulphur outside the cells;
(3) Sulphur and thiosulphates to sulphuric acid.

The physiology of these sulphur organisms was first studied in a classical investigation by Winogradsky[2] to which but little has been since added.

The first group occur commonly in water and in wet places—lakes, ponds, swamps, and sulphur springs. They are extraordinarily interesting: one is the largest known bacterium (20-33 μ wide and 42-86 μ long); others are coloured; some seem capable of photosynthesis.[3]

The second group is widely distributed in soil, wet areas, and water. Of the soil forms, *Thiobacillus denitrificans* is of interest because Beijerinck[4] regarded it as the natural connecting link between the sulphur-oxidising bacteria and the denitrifying bacteria, since their two activities proceed side by side. Another soil form, *Thiobacillus B.*, isolated by Waksman, plays a part in the reclamation of alkali soils.

[1] For studies of the first stage of the breakdown see H. L. A. Tarr, *Biochem. J.*, 1933, **27**, 1869.

[2] *Bot. Zeitg.*, 1887, **45**, 489.

[3] For descriptions see D. Ellis, *Sulphur Bacteria*, Longmans, Green & Co., 1932.

[4] M. W. Beijerinck, *Proc. K. Acad. Wetensch.*, Amsterdam, 1920, **22**, 899: see also D. I. Aquino, *Iowa St. Coll. J. Sci.*, 1931, **6**, 65.

The third group is small, only one member having been described,[1] *Thiobacillus thio-oxidans*, but it is one of the most remarkable organisms known because of its amazing tolerance of acidity; the optimum *p*H for the media is between 3 and 4. It oxidises sulphur to sulphuric acid and continues doing so till the *p*H value is below 0·6, *i.e.* stronger than 0·1 *N* H_2SO_4. It was also found by Jensen in a very acid (*p*H 2·2) sandy soil in Denmark, which contained free sulphuric acid and soluble iron compounds.[2] Bunker kept it in 7 per cent. sulphuric acid (*p*H 0·2) without serious harm.[3] It is strictly autotrophic, deriving its carbon entirely from CO_2, and its energy from the oxidation of sulphur, but how it can attack the solid particles remains a mystery. Advantage is taken of its properties in the United States to make the soil acid when needed; as, for example, in controlling potato scab (p. 544) and in the reclamation of alkali soils (p. 332).

The Reducing Organisms.—Under an aerobic condition reduction of sulphate to sulphide occurs. The process goes on in estuarine and lacustrine muds, but the organisms are widely distributed in soils. They were first seriously studied by Zelinsky and Brussilowsky in the Black Sea ooze. The characteristic *Vibrio desulphuricans* was described by Beijerinck,[4] and further studied by A. van Delden[5] and other workers in Holland. Some of these organisms are extremely interesting. One has its optimum growth temperature between 50° C. and 60° C. and ceases to act at 30° C. Unlike the oxidising organisms, these require neutral conditions.

The reduction of sulphur to hydrogen sulphide is not, like the preceding reactions, the specific properties of a few organisms, but appears to be brought about by a number of ordinary saprophytic bacteria, yeasts, and moulds.[6]

[1] S. A. Waksman and J. S. Joffe, *J. Bact.*, 1922, **7**, 239; R. L. Starkey, *J. Bact.*, 1925, **10**, 135, 165.

[2] *Zbl. Bakt.*, Abt. II, 1927, **73**, 242.

[3] For description of a less acid-tolerant form common in South Australia, see Phyllis Robertson, *Austral. J. Exper. Biol.*, 1932, **11**, 209.

[4] *Zbl. Bakt.*, Abt. II, 1895, **1**, 49 and 104.

[5] *Ibid.*, 1904, **11**, 81 and 113.

[6] J. de Rey-Pailhade, *C.R.*, 1888, **106**, 1683; **107**, 43.

Oxidation of Ferrous and Manganese Carbonates.

Certain bacteria are able to oxidise ferrous and manganese carbonates and thus to obtain their energy. Winogradsky [1] studied *Leptothrix* and Lieske [2] a *Spirophyllum;* both organisms can live without organic matter, deriving their carbon from carbon dioxide. How far they are important in the soil is not known; most of the technical studies having been in connection with waters.

Effect of Micro-organisms on Soil Phosphorus Compounds.

The organic phosphorus compounds in plant residues gradually break down in the soil and become converted into phosphates.

Mineral phosphates are dissolved under certain conditions by bacteria in culture solutions, but it is not certain how far this action goes on in soil: the evidence is presumptive only. Lupins can assimilate mineral phosphates that are too insoluble to serve for other plants, and this may be associated with their nodule bacteria, though not necessarily. Mineral phosphates are effective on degraded chernozems in spring when bacterial activity is considerable, but not in autumn.[3] More direct evidence is afforded by the fact that bacteria associated with the decomposition of farmyard manure can utilise, and therefore must dissolve, mineral phosphates.[4]

Modifications in Extreme Soil Conditions:

I. Arid Conditions.

The various changes described above occur in all soils, but their relative importance differs according to the conditions. In arid conditions the amounts of organic matter and of

[1] S. Winogradsky, *Bot. Zeitg.*, 1888, **46**, 262.

[2] R. Lieske, *Jahrb. wiss. Bot.*, 1911, **49**, 91; *Zbl. Bakt.*, Abt. II, 1919, **49**, 13.

[3] A. N. Lebediantzev in E. E. Uspensky, *Soil Microbiology in the U.S.S.R.*, Moscow, 1930.

[4] M. Tyagny-Ryadno, *J. Agric. Sci.*, 1933, **23**, 335.

nitrogen are both low, and vegetation is never sufficiently active to provide a dense covering such as occurs on the grasslands of temperate climates. Cultivation is not necessarily accompanied by a loss of nitrogen; indeed, instances occur where cultivated land is somewhat richer in nitrogen than the original virgin land. On the other hand lucerne is ineffective in raising the nitrogen content of the soil. Some results are given in Table 76.

TABLE 76.—PERCENTAGE OF NITROGEN IN SOILS IN ARID REGIONS.

	Eastern Oregon. C. E. Bradley.[2]			Cache Valley, Utah. R. Stewart.[1]
	(*a*)	(*b*)	(*c*)	
Virgin soil . . .	0·114	0·101	0·098	0·198
Cultivated land . .	0·107	0·102	0·102	—
Land mainly under wheat	—	—	—	0·206
Land under lucerne .	—	—	—	0·201

Azotobacter occurs commonly, and many observations suggest that it is actively fixing nitrogen. Limited areas are periodically found where the concentration of nitrate in the soil is very high: sometimes indeed so high as to inhibit the growth of vegetation:[3] Azotobacter has been claimed as the cause, though this is much disputed.

[1] *Utah Agric. Expt. Sta. Bull.* No. 109, 1910; first foot. In the second depth the cultivated soil had lost its nitrogen relative to the virgin soil, the loss under lucerne being greater than that under wheat.

[2] *J. Ind. Eng. Chem.*, 1910, **2**, 138. In cultivation for (*a*) twenty-five to thirty years, (*b*) seventeen years, (*c*) twenty-five years. The carbon had decreased in (*a*) from 1·53 to 1·17 per cent. and in (*b*) from 1·41 to 1·11 per cent. There had been no change in nitrogen in subsoil in (*a*) (0·081), and in (*b*) a fall from 0·094 to 0·090. The carbon had fallen in the subsoil of (*a*) from 0·986 to 0·754 and of (*b*) from 0·973 to 0·735. For comparisons of the nitrogen relationships in humid, sub-humid, and semi-arid regions of Kansas, see C. O. Swanson and W. L. Latshaw, *Soil Sci.*, 1919, **8**, 1; for studies in Arizona, J. E. Greaves, *Zbl. Bakt.*, Abt. II, 1914, **41**, 444; in South Africa, and comparison with American work, T. D. Hall, *Soil Sci.*, 1921, **12**, 301.

[3] R. Gardner, A. Kezer, and J. C. Ward, *Colo. Agric. Expt. Sta. Tech. Bull.* No. 6, 1934; E. P. Sandsten, *Colo. Agric. Expt. Sta. Bull.* No. 235, 1917.

2. Waterlogged Conditions: Swamp and Paddy[1] Soils.

The changes described in the foregoing sections are modified when the soil is waterlogged for long periods. Harrison and Aiyer[2] studied the decomposition of plant residues (green manures) in swamp conditions at Pusa. In the body of the soil, marsh gas, hydrogen, and CO_2 are evolved as would be expected from the anaerobic decomposition of cellulose. But at the surface of the soil the change is entirely different and the gases consist of oxygen and nitrogen only. The difference was traced to a film of organisms, including algæ, which have the power of converting the marsh gas into CO_2,[3] and this into oxygen. The oxygen is directly beneficial to the plant by providing for the aeration of the root. The production of oxygen was suppressed when the film was killed by adding copper sulphate: marsh gas and hydrogen then appeared at the surface.

It is only so long as the film is working that green manuring is beneficial to the crop. The plant roots must have oxygen and the film supplies it. The green manure, therefore, serves as a supplier of dissolved oxygen.

Subrahmanyan[4] at Rothamsted studied the decomposition of the nitrogen compounds in the plant residues working with a number of Indian and Rothamsted soils. He showed that waterlogging slightly decreased the bacterial numbers (using Thornton's agar) and the nitrate, but markedly increased the ammonia, the production of which he attributed to enzymic action.

When small quantities of easily fermentable substances,

[1] Swamp soils on which in the East—in India, Japan, and other countries—considerable quantities of rice are grown. There is, however, some movement of the water; the conditions are not as stagnant as in a peat bog.

[2] *India Dept. Agric. Mem. Chem. Ser.*, 1913, **3**, 65 and 1913, **4**, 1.

[3] The biological oxidation of marsh gas has been described by Kaserer and Söhngen, and by I. Giglioli and G. Masoni (Pisa: *Chim. Agric. Stud. e Ricerche*, 1909-1914, Part XXII, 76). For the effect of algæ see p. 419.

[4] V. Subrahmanyan, *J. Agric. Sci.*, 1927, **17**, 429, 449; 1929, **19**, 627.

e.g. glucose, were added the bacterial numbers increased, the nitrate and dissolved oxygen decreased, carbon dioxide and various organic acids (lactic, acetic, butyric) were produced. There was, however, no sign of denitrification: the nitrate was assimilated by the organisms but not reduced to gaseous compounds (p. 371).

The Japanese experimenters have studied the effects of nitrate of soda as a fertiliser on swamp soils. Nagaoka [1] showed that it frequently depresses instead of increasing the yields of rice, sagittaria, and juncus, an action which he attributed to the formation of poisonous nitrites by reduction. Daikuhara and Imaseki [2] developed this view and showed that the effects become especially pronounced when glycerine is added. Kelley obtained similar results with rice in Hawaii.[3] On the other hand, sulphate of ammonia, soy bean, and green manures all gave increased yields, and these fertilisers are used in practice, and not nitrate of soda, in swamp and paddy soils.

Summary.

The Effect of Adding Plant Residues to the Soil.

Organic matter is continuously being added to the soil by the vegetation that grows upon it: it is continuously being decomposed by living creatures in the soil, especially micro-organisms. An equilibrium is attained which alters but little so long as the conditions remain approximately the same, but it changes rapidly as soon as the conditions alter, and a new equilibrium is reached which again remains steady if the conditions remain steady once more. In any case the C/N ratio of the soil organic matter undergoes little change, being about 10 in temperate conditions, but higher in cold and lower in hot climates.

Under a close and permanent vegetation, as under grass

[1] M. Nagaoka, *Bull. Coll. Agric.*, Tokyo, 1904, **6**, 285.

[2] G. Daikuhara and T. Imaseki, *Bull. Imp. Central Agric. Expt. Sta.*, Japan, 1907, **1**, 7.

[3] *Hawaii Agric. Expt. Sta. Bull.* No. 24, 1911.

in temperate climates, the amounts of organic matter and of nitrogen in the soil remain high : in continuously cropped land they are low. Addition of organic matter to cultivated soils temporarily raises the nitrogen content, but decomposition proceeds rapidly, the ratio of the carbon to nitrogen, however, remaining at about its normal value.

In a given set of climatic conditions there is, therefore, an upper as well as a lower limit to the nitrogen content of the soil, the actual values depending on the soil conditions. Between these limits the nitrogen content may be maintained at any desired level, high when the ground is left in grass and leguminous crops, low when the ground is continuously cultivated. Unfortunately, on our present knowledge it is impossible to maintain a high content of nitrogen on cultivated land except at a wasteful expenditure of nitrogenous manure.

Some of these limits for English soils are :—

	Black Organic Soils (containing more than 10 per Cent. of Organic Matter).	Chalk Soils.[1]	Clays.	Loams.[1]	Sands.[1]
Upper limit .	3	0·42	0·35	0·25	0·20
Lower limit .	0·25	0·13	0·09	0·09	0·03

The nitrogen content of the virgin soils in Nebraska is similarly governed by the soil texture.[2]

The nitrogen cannot be increased by itself alone ; increases are possible only when the carbon is increased ; and the gain in nitrogen is only about one-tenth that of the carbon. Purely nitrogenous fertilisers, such as nitrate of soda, sulphate of ammonia, dried blood, etc., add no nitrogen to the soil beyond what corresponds with any carbon added by the stubble. On the Broadbalk plots to which sulphate of ammonia has been given annually since 1844 and nitrate of soda since

[1] Containing less than 10 per cent. of organic matter.

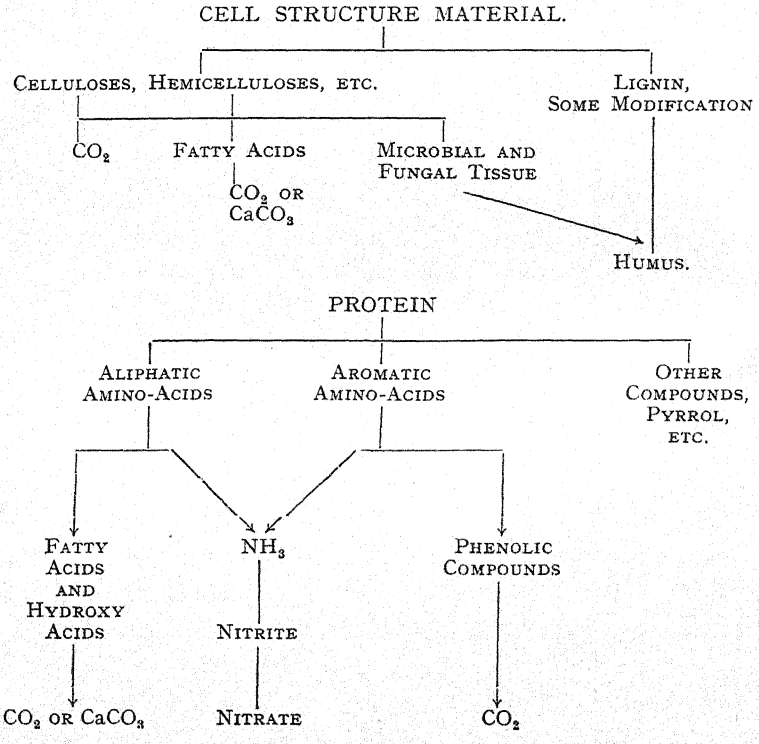
[2] J. C. Russel and W. G. McRuer, *Soil Sci.*, 1927, **24**, 421.

1852 the percentages of nitrogen and of carbon in the top 9 inches of soil were, in 1914 :—

		As Sulphate of Ammonia.			As Nitrate of Soda.	
Nitrogen added, lb. per acre	None	43	86	129	43	86
Nitrogen in soil, per cent. .	0·104	0·111	0·119	0·129	0·116	0·115
Carbon in soil, per cent. .	1·15	1·14	1·41	1·35	1·52	1·73

J. G. Lipman and A. W. Blair record losses of nitrogen from cropped soils in spite of added nitrogenous fertilisers.

Changes in climatic conditions, however, lead to changes in the level of the nitrogen content. A fall in mean temperature tends to raise the nitrogen content: a rise in temperature lowers it. The Gezira soil of the Sudan, a heavy clay, contains only 0·03 per cent. of nitrogen : similar clays in England



would contain 0·2 to 0·3 per cent. (pp. 238, 346). H. Jenny [1] finds that in North America a fall of 10° C. in mean temperature doubles or trebles the nitrogen content: the relation is almost exponential.

The general course of the decomposition is shown diagrammatically on page 408.

The immediate effects of adding plant residues to the soil depend on the proportions of carbohydrate and protein present.

If the conditions are favourable to the activity of micro-organisms the result of the addition is to cause an increase in numbers and in activity of the micro-organisms: this is shown by increases in oxygen absorption and CO_2 evolution. The increase is rapid if the material is easily decomposed (*e.g.* clover residues), but it is soon followed by a fall; it is slower but longer sustained if the material is less easily decomposed (*e.g.* timothy residues).[2] The increased numbers may have any of the following effects:—

(1) If the material is rich in energy supply but not in nitrogen (*e.g.* carbohydrates), the organisms may assimilate nitrates or ammonia already existing in the soil and thus reduce the amounts of these substances present (p. 349). These circumstances are favourable to the nitrogen-fixing bacteria, and if the temperature is sufficiently high there may be an increase in the amount of nitrogen fixed (p. 474). The assimilation effects are temporarily harmful, but the fixation is ultimately beneficial to the growing plant. Fig. 44 shows the various changes when straw is added to the soils.

(2) If the material is rich in nitrogen (*e.g.* protein), the organisms will produce considerable quantities of ammonia in obtaining their energy supplies. The ammonia is then converted into nitrate. This effect is wholly beneficial to the plant.

[1] *J. Amer. Soc. Agron.*, 1928, **20**, 900.

[2] B. D. Wilson and J. K. Wilson, *Cornell Agric. Expt. Sta.*, Memoir 95, 1925.

The nitrate is the most easily lost of all the nitrogen compounds in the soil. It is liable to be leached out, absorbed by plants or decomposed. Losses of nitrogen are particularly liable to occur when much nitrogenous organic matter is present (p. 345).

The net result of these various activities is that the ratio of carbon to nitrogen in a soil is not easily disturbed; in humid conditions it is about 10. Addition of non-nitrogenous

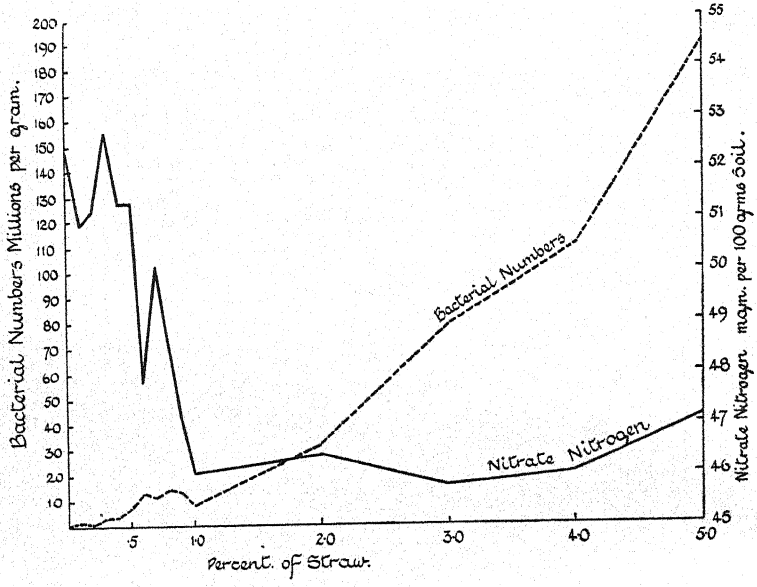
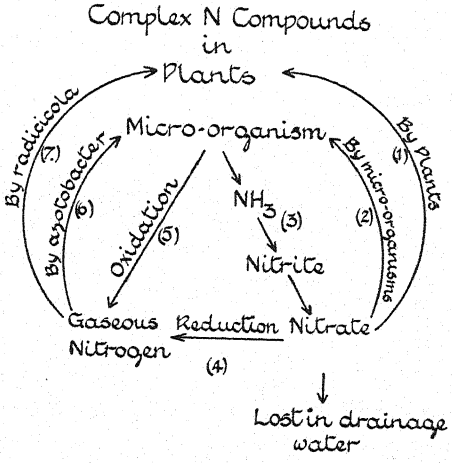


FIG. 44.—Effect of straw on soil biological processes after twelve weeks at laboratory temperature (about 21° C.; T. J. Murray, *Soil Sci.*, 1921, **12**, 233).

organic matter, such as starch, cellulose, or straw (which is poor in nitrogen) sets in train the process of nitrogen fixation which increases the amount of nitrogen at the expense of a much larger amount of carbon, and also the microbiological assimilation of nitrates, which, while reducing the amount of carbon, protects the nitrogen already present against loss. Both sets of processes decrease the carbon and increase the nitrogen, thus restoring the original ratio.

Addition of nitrogenous organic matter at first increases the proportion of nitrogen and it causes the bacterial numbers at once to rise.[1] Nitrification then takes place: the nitrates are easily lost. The loss of nitrogen proportionately exceeds that of carbon, so that again the original ratio is restored.

(3) If the air supply is insufficient—either generally or locally—but other conditions are favourable, the organisms may obtain some of their oxygen from the nitrates present



There is but little direct evidence that (4) or (5) take place in soil.

FIG. 45.—Scheme showing the fate of nitrogen during the growth and decomposition of plants in soil, so far as is at present known.

in the soil, reducing them to nitrites. This effect is wholly harmful to the plant (p. 406). Ammonia accumulates, partly, apparently, as the result of enzyme action.

(4) If, however, conditions are unfavourable (*e.g.* if there is acidity or too low a temperature) the organisms become less active: the material partly decomposes and it accumulates as peat (p. 342).

[1] See H. L. Jensen, *J. Agric. Sci.*, 1931, **21**, 38, for curves showing bacterial increases prior to nitrate increases when farmyard manure is added to soil.

The changes in the nitrogen compounds are represented diagrammatically in Fig. 45. Many of the changes closely resemble those occurring during sewage purification, as worked out by Adeney [1] and Fowler,[2] one of the main differences being that they proceed more quickly in sewage than in soil.

These changes are mainly brought about by micro-organisms, some of them through the action of enzymes.

[1] *5th Rept. Royal Commission on Sewage*, 1908, Appendix VI.
[2] *Bacteriological and Enzyme Chemistry*, London, 1911.

CHAPTER VI.

THE MICRO-ORGANIC POPULATION OF THE SOIL AND ITS RELATION TO THE GROWTH OF PLANTS.

THE investigations described in the last chapter have shown that the soil contains many micro-organisms capable of effecting changes of great importance to the living plant. The organisms first discovered were bacteria, and for some long time these were regarded as the only living microscopic occupants of the soil. Later work has revealed many other forms, including fungi and actinomycetes, algæ, protozoa, and nematodes. These have usually been picked out from the soil by cultural methods and studied in the laboratory; little is yet known of the way in which they live in natural conditions in the soil.

The older conception of the soil population arose quite naturally from the way in which it first came into prominence. It was supposed to be engaged in producing plant food and to be made up of groups of specialised organisms, each capable of effecting certain changes. The following were recognised :—

1. Ammonifying.
2. Nitrifying.
3. Nitrogen fixing.
4. Denitrifying.
5. Pectin fermenters.

Their actions in the soil were deduced from the results of laboratory culture experiments, and values were assigned to the "ammonifying power," "nitrifying power," etc., which were used in comparing different soils and manures. This method of investigation was introduced by Remy,[1] and developed by Löhnis[2] and J. G. Lipman;[3] it achieved

[1] Th. Remy, *Zbl. Bakt.*, Abt. II, 1902, 8, 657.
[2] *Zbl. Bakt. Abt. II*, 1904, **12**, 262, and later papers.
[3] *N.J. Agric. Expt. Sta., 25th Ann. Rept.*, 1904, 237.

considerable popularity because of the ease and simplicity of its manipulation.

The " nitrifying power " was measured by putting a definite weight of the soil into Omeliansky's or Ashby's medium (p. 367), incubating under definite conditions and determining the amount of nitrate formed. For measuring " ammonifying power " 1 per cent. peptone solution was used, and for the " nitrogen-fixing power " Beijerinck's or some similar solution.

The method had a certain value for the testing of soils, and there was usually some relationship between the various " powers " and the productiveness. On the whole, the " nitrifying " and " nitrogen fixing " powers were most nearly related to productiveness and " ammonifying power " least.[1] But the indications were never very certain; the exceptions could not usually be explained and little useful information emerged.

In addition to these attempts at finding an integration or summation value of the activities of the soil population, bacteriologists attempted to study the members themselves. Methods for isolating the organisms forming the various groups were devised, usually on the lines of Winogradsky's " elective " method (p. 382), and they led to some striking discoveries, particularly of organisms limited in their range of activities (like the nitrifying organisms) or possessing some special property, such as the power of fixing nitrogen or oxidising phenol, that enables them to survive when others perish.

Further investigations showed, however, that these cultural methods do not give a true picture of the population of organisms as they live and work in natural soil. In the first place, many of the organisms exist in two states, one active or trophic, and the other resting or comparatively inert. The line between them may not be sharp, and there

[1] The position is reversed with alkali soils. For later critical studies see S. A. Waksman, *Soil Sci.*, 1923, **16**, 55; of the older papers see P. Ehrenberg, *Landw. Jahrb.*, 1904, **33**, 1-139.

may be constant change from one to the other as the conditions in the soil vary. Culture methods do not discriminate between those organisms which are active in the soil, and those which are simply resting.

Further, it was found that only few of the soil organisms are limited to one type of activity; most of them have considerable powers of changing their actions when the conditions alter. The grouping into ammonifiers, nitrogen fixers, etc., therefore had no significance in the soil, and meant nothing more than that the organisms could, in the particular conditions of the experiment, bring about the particular changes observed. The method had a certain validity when applied to the specialised nitrifying organisms, and its indications showed some relation to the facts of soil fertility. But it did not hold well for ammonia production, this being a property shared by many organisms.

A new conception of the activities of the soil population has therefore grown up. The organisms are now studied, not merely as producers of plant food, but as independent forms of life seeking food and energy material and possessing a range of choice in their quest. They may effect one change under one set of circumstances, but another change under other circumstances. Some of the organisms have a wide choice, others are more limited. The action most conspicuous in culture media is not necessarily the customary action in the soil. Nothing but studies in the soil itself can show which particular phases of activity are usual in the soil. The outcome of the development of this idea is that investigators are devising methods for work in the soil in addition to the work (which must necessarily always continue) with culture media in the laboratory.

Several methods have been introduced for this purpose :—

(1) A method of direct microscopical examination in the field has been used by W. Kubiena of Vienna, but as it requires special equipment it has not yet been widely tested.[1]

[1] *Arch. f. Mikrobiol.*, 1931, **3**, 507; *Soil Res.*, 1932, **3**, 91.

(2) The numbers of bacteria in the soil are estimated and are studied in relation to other quantities. The work has to be done under proper statistical control as it is beset with many difficulties.

The old method of counting was to pour a suspension of the soil on to a plate of nutrient gelatine or agar, allow the bacteria to multiply, and then count the colonies formed. Many organisms, however, fail to develop on these plates and the numbers obtained were considerably lower than those given by the direct method.

Much higher and truer estimates of the numbers are obtained by examining under the microscope thin films of the soil, stained by a method that permits of discrimination between micro-organisms and other soil constituents: *e.g.* the staining techniques of Conn, Winogradsky, or Koffman (Sweden). The quantitative estimates of Rothamsted are made by the ratio method of Thornton and Gray.[1] These counts show how the numbers of organisms vary but the method does not enable physiological groups of the soil bacteria to be distinguished, nor does it allow pure cultures to be isolated: for morphological and physiological investigations it must be supplemented by plating upon selective media, followed by studies in pure culture.

Cholodny, Rossi, and Ziemięcka had developed a different method of examination.

(3) Rossi and Cholodny have independently devised methods for direct examination of the organisms in the soil. Cover slips, either clean or coated with various chemotactic substances, are buried in the soil: after a few days they are recovered and examined microscopically. Alternatively soil is packed into glass cells with a small clear central area, through which the organisms can be observed as they move out from the soil particles.[2] The method has been used by

[1] H. G. Thornton and P. H. H. Gray, *Proc. Roy. Soc.*, 1934, B, **115**, 522.

[2] N. Cholodny, *Arch. Mikrob.*, 1930, **1**, 620; 1934, **5**, 148.

G. Rossi [1] to estimate the relative preponderance of the organisms present, and by Jensen [2] to estimate the densities of fungal mycelium, thus overcoming the objections inherent in the "counts" of fungal tissues (p. 423). J. Ziemięcka [3] has modified it to follow the sequence of organisms attacking substances introduced into the soil.

(4) Winogradsky has devised a method, the *plaque moulée*, in which some of the soil is kneaded up in a Petri dish and treated with a culture solution that induces development of the particular group of organisms under investigation. The method in various modifications has been used for assessing the phosphate or lime requirements of soils (see p. 475). The modified silica jelly plates of Helen Winogradsky have proved valuable for discovering new types of organisms.

The Algæ.

The soil has a characteristic algal flora which appears to be substantially the same in general type all over the world so far as investigation has gone. B. M. Bristol-Roach (1920, 1927) finds that the central group of almost universal occurrence includes *Hantzschia amphioxys*, *Trochiscia aspera*, *Chlorococcum humicola*, *Bumilleria exilis*, and rather less frequently, *Ulothrix subtilis* or types similar to these.[4] In a detailed study of four English soils she found no fewer than thirty-five species, some of which, however, were not true soil forms but only casuals. This same central group was also found in the soils of Victoria (Australia).[5]

Algæ grow and multiply in two very different conditions in the soil :—

[1] Giacomo Rossi's papers (1928 onwards) are mainly in journals not easily accessible, but he has given a full account in *Soil Sci.*, 1936, **41**, 53.

[2] *Proc. Linn. Soc. N.S.W.*, 1936, **61**, 27.

[3] *Rocz. Nauk Roln.*, 1934, **33**, 23.

[4] See also F. E. Fritsch, *J. Ecology*, 1922, **10**, 220.

[5] Jean Phillipson, *Proc. Roy. Soc. Victoria*, 1935, **47**, 262.

(1) On the surface exposed to light, where, by means of their chlorophyll, they fix the energy of sunlight and assimilate carbon dioxide, thus producing complex organic matter. In these conditions the algæ are suppliers of energy material to the soil, and they assimilate nitrates and other nutrients from the soil just as green plants would do.

(2) In the depths of the soil beyond the reach of light, where the chlorophyll ceases to function (though it may still remain in being) and the organisms obtain their energy and carbon from preformed organic matter; *i.e.* they live saprophytically. They now become consumers of the soil stock of energy material. In Dr. Bristol-Roach's experiments the soil algæ always retained this property of assimilating complex organic matter, even when living in light, as on the surface of the soil. The chlorophyll apparatus may, therefore, be regarded as supplementary, coming into play when light is available, but not otherwise.

Of the organic substances tested, the hexose sugars were the most suitable nutrients. The nitrogen is usually assimilated as nitrate, but some soil algæ can assimilate ammonia and a few can attack protein (gelatine) direct.

Although its general types persist, the algal flora varies somewhat in different soil conditions. These ecological aspects were studied by Esmarch [1] in his pioneering investigation of the blue-green algæ of certain African and German soils; other workers are quoted by Dr. Bristol-Roach in the Rothamsted Monograph.[2] The blue-green algæ are more in evidence in warmer, and the green algæ in cooler, conditions; both, however, require sufficient moisture. On the Rothamsted arable fields the floral type is not obviously affected by the manuring, but the numbers of organisms are smallest on

[1] F. Esmarch, *Jahrb. Hamburg. Wiss. Anst.*, 1910, **28**, 3 Beiheft, 62; *Hedwigia*, 1914, **55**, Heft 4-5.

[2] *The Micro-organisms of the Soil*, Longmans, 1923. For recent studies of algæ in soils see D. Fehér and M. Frank, *Arch. Mikrobiol.*, 1936, **7**, 1.

the unmanured plot and largest on the one receiving farmyard manure ; this holds also for surface growth. The Rothamsted grassfields have not been examined, but Esmarch found more species in grassland than in arable ; blue-green algæ, however, appear to be commoner in arable land than in grassland, though their frequency was reduced by frequent cultivation, while diatoms—usually very small ones—occur in numbers in old gardens. The influence of soil reaction was examined by J. B. Petersen in Denmark ; he showed that the flora of acid soils was dominated by *Mesotænium violascens*, *Zygnema ericetorum*, and two species of *Coccomyxa*, while the flora of neutral soils was largely *Mesotænium macrococcum*, *Hormidium* and *Vaucheria*.

The activities of soil algæ important to plant growth appear to be :—

(1) The addition of organic matter to the soil. This action is confined to the surface growth and is dependent on light. It is valuable in most circumstances, but on newly formed soils it is of the greatest importance. After the destruction of soil and vegetation of Krakatoa by volcanic eruption in 1883 the first colonists of the barren mineral layer were six species of blue-green algæ, *viz.* *Tolypothrix*, *Symploca*, *Anabæna*, and three species of *Lyngbya*, which gradually spread over the whole surface, and made the beginning of a soil on which seeds brought by birds could grow.[1] Fritsch has also given examples of colonisation of new ground in Ceylon.

(2) The fixation of nitrogen (pp. 382, 420).

(3) Symbiosis with Azotobacter, leading to an increase in the amount of gaseous nitrogen fixed (p. 382).

(4) The assimilation of easily oxidisable organic matter, *e.g.* sugars.

(5) In swamp soils algæ facilitate aeration of the roots by decomposing the CO_2 dissolved in the water and liberating

[1] Treub, *Ann. Jard. Bot. Buitenzorg*, 1888, **7**, 221-223. This has been somewhat qualified recently by C. A. Barker, *The Problem of Krakatoa as seen by a Botanist* (M. Nijhoff, The Hague, 1930).

oxygen, which still remains in solution. Brizi[1] observed that the *brusone* disease of marsh rice, which he attributed to inadequate aeration of the roots, did not appear when algæ developed plentifully on the surface of the marsh (p. 405).

Some of the algæ have been credited with the power of fixing gaseous nitrogen, but except perhaps for *Nostoc* (p. 382) this is probably incorrect.[2]

The numbers of the green algæ in the soil can be roughly estimated by an appropriate dilution method, but the blue-green forms cannot yet be counted. The estimate is not sufficiently trustworthy to allow of the application of statistical methods, but minimum values of the order of 100,000 green algæ per gram of soil have been recorded by Dr. Bristol-Roach, and the blue-green forms may be equally numerous. The numbers differ in the different layers of the soil; they are usually at a maximum in the surface inch, lower in the second and third inches, much higher in the fourth inch, then at lower depths they fall off and in the subsoil probably occur only as spores. In the first four or five inches, however, most of the algæ are present in the vegetative rather than the spore form.[3] Treating the cells as if they were spheres of radius 10 μ (which is not far out), the mass of algal protoplasm is about one-third that of the protozoan population of the soil.

Francé[4] claimed that the numbers of algæ in the soil reach a maximum in the spring which, if true, would accord with the behaviour of bacteria and protozoa.

[1] U. Brizi, *Annuario Istituz. Agrar.*, Milan, 1906, **6**, 59-103, esp. pp. 84-89; 1908, **7**, 107-174; see also W. H. Harrison and S. Aiyer, *India Dept. Agric. Mem.*, Chem. Ser., 1913, **3**, 65, and 1914, **4**, 1.

[2] Discussed long ago by Gautier and Drouin, *C.R.*, 1888, **106**, 754 *et seq.* B. Muriel Bristol (now Bristol-Roach) and H. J. Page, *Ann. Appl. Biol.*, 1923, **10**, 378.

[3] B. M. Bristol-Roach, *J. Agric. Sci.*, 1927, **17**, 563; *Proc. 1st Int. Cong. Soil Sci.*, Washington, 1927, **3**, 30, where the results of the Rothamsted investigations are summarised.

[4] *Das Edaphon*, Stuttgart, 1921.

Lichens.[1]

Lichens are not single organisms, but close structural associations between algæ and fungi. The type of association varies, but each pair is sufficiently distinct to be recognisable as a lichen species. Lichens have not been found in the soil, but the terricolous group lives on the surface of poor soils, and presumably adds to the supply of soil organic matter. The saxicolous group lives on bare rock and may play a part in formation of soils; while other lichens, which decompose bark, dead wood, etc., may assist in the formation of humus. Lichens are often studied along with the bryophytes (mosses).

Fungi.

It has long been known that fungi occur in the soil, and as long ago as 1886 eleven different species were isolated by Adametz.[2] Subsequent workers have greatly enlarged the list and several hundred species have now been described.

The investigations have fallen into several groups. Some workers, as Butler[3] in India, Hagem[4] in Norway, and Lendner[5] in Switzerland, have confined themselves mainly to particular types, and have not attempted a comprehensive survey of the whole field.

Others have studied the saprophytic life of such parasitic forms (*e.g.* species of Fusarium and Pythium) as can maintain themselves in the soil. Pratt[6] has isolated fungi from virgin

[1] For further information see A. L. Smith, *Lichens*, Cambridge Univ. Press, 1921; O. V. Darbishire, *J. Ecology*, 1914, **2**, 71; and W. Watson, *ibid.*, 1918, **6**, 126 and 189.

[2] L. Adametz, "Untersuchungen über die niederen Pilze der Ackerkrume," *Inaug. Diss.*, Leipzig, 1886.

[3] E. J. Butler, *India Dept. Agric. Mem.*, Bot. Ser., 1907, **1**, 1-160.

[4] O. Hagem, "Untersuchungen über norwegische Mucorineen," *Videns Skrift*, I, *Math. Nat. Kl.*, 1907, No. 7; Part II, 1910, No. 4.

[5] A. Lendner, *Les Mucorinées de la Suisse*, Berne, 1908.

[6] O. A. Pratt, *J. Agric. Res.*, 1918, **13**, 73.

desert lands which cause disease in potatoes, and also from Idaho soils that have never been cropped with potatoes.

The more serious problem of studying the fungus flora of the soil as a whole has been attempted in Holland by Oudemans and Koning,[1] in the United States by C. N. Jensen at Cornell,[2] Waksman in New Jersey,[3] J. C. Gilman and E. V. Abbott in Iowa,[4] in Denmark by H. L. Jensen,[5] in Russia by A. Rayllo,[6] and in England by E. Dale[7] and by W. B. Brierley at Rothamsted.

From these investigations it appears that a group of fungi occurs so commonly in the soil as to constitute a soil flora, and, as happens with protozoa and bacteria, this flora includes representatives of certain species which occur in widely separated parts of the world: the relative proportions characteristic of the soil habitat, however, vary considerably according to the conditions.

This general group characteristic of the soil habitat includes the genera Penicillium, Mucor, Aspergillus, Trichoderma, Fusarium, Verticillium, Cephalosporium, and Monilia, with many others occurring in smaller number or less frequently. In temperate conditions the Penicillia sometimes out-number all the rest and may form more than 50 per cent. of the entire flora. In warmer conditions, however, the Aspergilli may be the most numerous: *e.g.* in glasshouse soils, garden soils, in the Southern United States.[8] H. L. Jensen[9] found that the floras in Danish soils fell into two groups: those on field soils, marsh soils, and uncultivated mineral soils characterised by

[1] *Arch. Néerland. Sci. Exact. et Nat.*, 1902 [2], **7**, 266.

[2] *Cornell Agric. Expt. Sta. Bull.* No. 315, 1912.

[3] *Soil Sci.*, 1916, **2**, 103; 1918, **6**, 137. See also his *Principles of Soil Microbiology*, 1932.

[4] *Iowa St. Coll. J. Sci.*, 1927, **1**, 225.

[5] *Soil Sci.*, 1931, **31**, 123.

[6] Working in A. A. Jaczevsky's laboratory, Lenin Institute, 1928.

[7] *Ann. Mycol.*, 1912, **10**, 452; and 1914, **12**, 32. For an interesting local survey see Jessie S. B. Elliott, *Ann. Appl. Biol.*, 1930, **17**, 284.

[8] S. A. Waksman, *Soil Sci.*, 1917, **3**, 565.

[9] *Ibid.*, 1931, **31**, 123.

abundance of Mucoraceæ, and those on the more acid forest, moor, and heath soils characterised by numerous Trichodermæ.

Some of the soil forms are parasitic in plants, and may be found in greater abundance where their host plants are growing than where they are not. Reinking divided the tropical soil Fusaria into two classes, true soil fungi and soil invaders. The latter are dependent on the host plant for their continued existence in the soil, and in its absence they gradually decline and die out. He found a close relation between the severity of the banana wilt disease and the occurrence of the pathogen, *Fusarium oxysporum f.* 3, in different types of soil.[1] Jagjiwan Singh at Rothamsted found Fusaria more abundantly on the Broadbalk wheat field than on the mangold field. It has been claimed that the repression of the parasitic fungi is facilitated by a vigorous development of the saprophytic organisms: dressings of farmyard manure, for instance, greatly increased the saprophytic population on the irrigated cotton plots of the Arizona field station, but repressed the root rot fungus (*Phymatotrichum omnivorum*) so that it showed less on the Cholodny slips, and it also attacked the plants less.[2]

Other fungi form more beneficial relationships, such as the mycorrhiza (p. 426). One fungus (*Pyronema confluens*) seems specially favoured by something produced when soils are heated above 100° C. and grows strongly on sterilised or burnt soils.[3]

No direct method of examination of fungi in the soil has been devised such as is used by Winogradsky and Thornton for soil bacteria, but the Rossi-Cholodny technique gives information about the growth of different species in almost natural conditions. For quantitative studies plate culture methods are used; none of these permits an estimate of the total numbers of fungi in the soil, but a standardised technique

[1] *Zbl. Bakt.*, Abt. II, 1934, **90**, 4, and 1935, **91**, 243.

[2] C. J. King, Claude Hope, and E. D. Eaton, *J. Agric. Res.*, 1934, **49**, 1093.

[3] For a detailed study see W. Robinson, *Ann. Bot.*, 1926, **40**, 245

has been worked out at Rothamsted by Brierley and his colleagues [1] which gives consistent and comparable results. It misses, however, organisms that only slowly form colonies on the culture plates, *e.g.* the Basidiomycetes and most of the Ascomycetes and those fungi which do not grow easily on solid media, such as many of the Phycomycetes, and there is, as yet, no means of knowing how many of these particular forms occur in the soil. Incomplete as they are, however, the numbers are high: Waksman obtained numbers of the order of 30,000 to 900,000 per gram of soil, H. L. Jensen obtained 24,000 to 46,000, while Brierley's counts, using improved methods, are of the order of 1,000,000 per gram of soil.

Less significance attaches to fungus counts than to bacterial counts, however, since the numbers obtained are determined much more by the sporing capacity of different forms than by the mycelial stage which, however, is the most active in the soil. H. L. Jensen [2] in his important studies of the fungus flora of Australian soils used both the Cholodny and the plate methods, combining them so that each largely compensated the disadvantages of the other. Certain broad relations can be traced between the numbers and the soil conditions.

Fungi are much affected by the air supply. They are more numerous in the surface layers than lower down in the soil. Jensen in Denmark found many more fungi in well-aerated sandy soils than in badly-aerated heavy clays or marsh soils.

Soils rich in organic matter give higher numbers than soils containing less organic matter.

The soil reaction has less effect on fungi than on the bacteria developing on plating media: their numbers may even be somewhat increased as the soil becomes acid and depressed when lime is added. The general result is that fungi preponderate in acid and uncultivated soils, while bacteria become numerically much more important in neutral and cultivated

[1] W. B. Brierley, S. T. Jewson, and M. Brierley, *Proc. 1st Int. Cong. Soil Sci.*, Washington, 1927, **3**, 48.

[2] H. L. Jensen, *Proc. Linn. Soc. N.S.W.*, 1934, **59**, 200; 1936, **61**, 27.

soils, as was pointed out many years ago by Ramann (1911). Some of Jensen's results are given in Table 77. He shows

TABLE 77.—EFFECT OF $CaCO_3$ ON NUMBERS OF FUNGI, ACTINOMYCETES, AND BACTERIA IN SOILS AS FOUND BY PLATING METHODS: PER GRAM. JENSEN[1] (DANISH SOILS).

	Heath Soil.				Sand Soil.				Light Loam.			
	*p*H.	Fungi, Thousands.	Bacteria + Actinomycetes, Millions.	Actinomycetes, per Cent.	*p*H.	Fungi, Thousands.	Bacteria + Actinomycetes, Millions.	Actinomycetes, per Cent.	*p*H.	Fungi, Thousands.	Bacteria + Actinomycetes, Millions.	Actinomycetes, per Cent.
Untreated soil	3·7	610	0·84	0	4·7	341	5	61*	5·8	127	8	36
$CaCO_3$ added	7·5	393	398	21	7·6	365	23	35	7·6	120	17	20

that the ratio of the numbers of fungi to bacteria and actinomycetes is closely correlated with the hydrogen-ion concentration of the soil, although the actual numbers are not.

The part played by fungi in the decomposition processes in the soil is that they are of all soil organisms the most economical in their metabolic processes, transforming into their body substance more of the carbon of the compounds they attack, and dissipating less of it as CO_2 than any other group of organisms in the soil: they assimilate more of the nitrogen from protein and leave less of it as ammonia, than do the bacteria. They may transform into fungal tissue as much as 50 or 60 per cent. of the compound decomposed.

They utilise carbohydrates for both energy and tissue formation. Some of them are active decomposers of cellulose: Penicillium and Trichoderma in somewhat acid soils; Mycogone, Botryosporium, Stachybotrys, and other common forms in neutral conditions (p. 354). In these circumstances, however, the bacteria play an important part. The Mucoraceæ have little or no power of attacking cellulose. The soil fungi

[1] *Soil Sci.*, 1931, **31**, 123.

can obtain their nitrogen from ammonia, nitrates, amino-acids, or protein: Czapek [1] considered that amino-acids were the most economical source. Proteins serve not only as a source of nitrogen but, in the absence of sufficient carbohydrates, they furnish energy and body-building material also, though in this case more degradation of protein takes place than is necessary to supply the nitrogen required, and hence ammonia remains over.[2] While fungi can assimilate ammonia and change it into protein they have no power of converting it into nitrite or nitrate, nor has it been proved that any of them can fix gaseous nitrogen excepting, perhaps, *Phoma radicis*, the mycorrhiza associated with the Ericaceæ (p. 427).

Fungi have several important effects on soil fertility. They keep the decomposition processes going when the conditions are too acid for actinomycetes and bacteria to act effectively; so they widen the range over which the normal soil processes go on. The decomposition of cellulose is of special importance, because the unchanged cell structure material may be harmful by opening up the soil too much and facilitating the evaporation of moisture. The assimilation of ammonia and nitrate, so long as it involves no competition with the growing plant, is useful in saving these compounds from loss by leaching. Fungi play an important part in the formation of humus (pp. 353, 363).

Mycorrhiza.

Certain soil fungi infect the roots of higher plants, but instead of being injurious they live temporarily in symbiosis with their hosts, which, however, eventually digest and absorb them.

In the case of many trees, especially forest trees, this special

[1] *Beitr. Chem. Physiol. u. Path.*, 1901-1902, **1**, 538; **2**, 557; **3**, 47. See also A. G. Norman, *Ann. Appl. Biol.*, 1931, **18**, 244. For differences in the ability of fungi to assimilate nitrate, see M. Volkonsky, *Ann. Inst. Pasteur*, 1934, **52**, 76.

[2] S. A. Waksman, *J. Agric. Sci.*, 1924, **14**, 555.

association between fungus and root is often characterised by the formation of a thick weft of fungus hyphæ surrounding tufts of short lateral roots. The name mycorrhiza, or fungus root, was first used for these tufts by Frank. When the fungus lives outside the root cells it is called *ectotrophic*. Numerous common Basidiomycetes can act as mycorrhiza, although certain trees are commonly associated with certain species of fungi.[1] Frank and others considered that the relation was mutually beneficial, the fungus contributing nitrogen compounds and possibly salts to the tree, while the tree supplied the fungus with carbohydrates; this view is supported by the recent work of M. C. Rayner [2] on the beneficial effect of mycorrhiza for various species of *Pinus* on poor heath soils in England. Others, however, regard the association as one of controlled parasitism. M. C. Rayner emphasises the dependence of successful mycorrhiza formation on favourable soil conditions, suitable to the fungus as well as to the host and the danger in poor soil conditions of the replacement of mycorrhiza by pseudo-mycorrhiza in which the fungus may become a mild parasite.

Endotrophic mycorrhiza, the fungal symbionts of which live within the cells of the root, have been described for many other plants. The best known, thanks to M. C. Rayner's investigations, is the heath *Calluna*, in which the endophyte is *Phoma radicis callunæ*. It has been claimed that this fungus can fix free nitrogen,[3] but further confirmation is desirable.

The roots of many species of herbaceous and other plants are frequently infected to a greater or less extent by an endophytic fungus with non-septate mycelium usually referred to as endotrophic mycorrhiza of the phycomycete type, which, after passing through the outer cortex, forms characteristic,

[1] E. Melin, *Untersuchungen über die Bedeutung der Baummycorrhiza*, Jena, 1925.

[2] M. C. Rayner, *Forestry*, 1934, 8, 96. For a general account of mycorrhiza see *New Phytol.*, Reprint 15, 1927.

[3] W. Neilson Jones and Llewellyn Smith, *Brit. J. Expt. Biol.*, 1928, 6, 167.

much-branched organs known as arbuscules near the endodermis. An unusually abundant development of the fungus has in several instances been associated with poor condition of its host plant. O'Brien and M'Naughton [1] regarded it as a parasite of strawberries in Scotland, and Reed and Frémont [2] in California showed that it acted as a parasite in the roots of citrus trees unmanured for a number of years, but that it was held in check in the roots of well-manured trees. The fungus has not yet been isolated and grown apart from the host plant, and it is at present doubtful whether it benefits its host.

Actinomycetes.

These organisms have affinities both with the bacteria and with the fungi, but their classification is very difficult. They grow on gelatine and agar plates and may indeed form 20 to 30 per cent. of the colonies appearing thereon; they were formerly often confused with bacteria till Beijerinck (1900), and afterwards Hiltner and Störmer (1903) drew attention to their presence. A. Krainsky [3] made a preliminary classification, but the first important soil studies were by Waksman and Curtis [4] and by Conn.[5] H. L. Jensen has studied the forms occurring in Danish and Australian soils; he shows that in New South Wales they tend to predominate under conditions of low moisture content and high temperature.[6]

At Bangalore in India, Subrahmanyan concluded that the actinomycetes occur in the soil only as conidia and not as vegetative mycelium. He obtained numbers of the order of one to three millions per gram.[7]

[1] D. G. O'Brien and E. J. M'Naughton, *West of Scotland Agric. Coll. Res. Bull.* No. 1, 1928.

[2] H. S. Reed and T. Frémont, *Phytopath.*, 1935, **25**, 645.

[3] *Zbl. Bakt.*, Abt. II, 1914, **41**, 649.

[4] *Soil Sci.*, 1916, **1**, 99; 1918, **6**, 309; 1919, **8**, 71.

[5] *N.Y. St. Agric. Expt. Sta. Tech. Bull.* No. 60, 1917.

[6] H. L. Jensen, *Proc. Linn. Soc. N.S.W.*, 1934, **59**, 101; 1936, **61**, 27.

[7] *J. Indian Inst. Sci.*, 1929, A, **12**, 53 (with R. V. Morris); *ibid.*, 253 (with M. G. Rao).

The group includes a large number of varieties difficult to characterise, nevertheless certain forms seem to occur regularly in most of the soils examined. They are very numerous in the soil: although the counting methods are incomplete their numbers vary from a few thousands up to 10-15 millions per gram of soil. Unlike the fungi they are very sensitive to acidity and are almost suppressed in soils of *p*H 4·6 or less: the highest numbers occur over the range *p*H 6·8 to 8·0. They utilise carbohydrates and protein as food and energy material; some of them make characteristic pigment, and a few produce distinctive odours. Some play a part in the decomposition of cellulose, coming in apparently towards the end of the reaction (p. 354); others decompose such resistant substances as soil humus, lignin, and keratin.[1] Most of them can reduce nitrate to nitrite under suitable conditions in culture media. Certain forms, *e.g. A. scabies*, are serious parasites on root crops. The characteristic odour of soil has been ascribed to the activity of actinomycetes.

There seems little doubt that actinomycetes play an important part in the soil processes, and full study is desirable.

Myxobacteria.

These organisms are characterised by the production of slime. They are commonly classed with the bacteria, but they have a more complex organisation and probably, like the actinomycetes, they lie between the bacteria and the fungi. Most of the recent work on the myxobacteria is due to Helena and Seweryn Krzemieniewski, who found them widely distributed throughout the soils of Poland, and indeed consider them as normal inhabitants of the soil.[2] Some of them readily decompose cellulose aerobically, obtaining their nitrogen from the nitrates or ammonia (p. 357). Apparently

[1] H. L. Jensen, *Soil Sci.*, 1930, **30**, 59; 1931, **31**, 123.

[2] H. Krzemieniewska and S. Krzemieniewski, *Acta Soc. Bot. Polon.*, 1927-1928, **5**, 79 and 102.

they contribute to the odour of soil, as all the Polish species give off an odour much resembling that of fresh earth.[1]

Bacteria.

Historically, bacteria are by far the most important group of organisms in the soil. They were the first to be isolated, and for long were regarded as the only organisms important in normal conditions; laboratories and departments were therefore set up for their study in most of the agricultural research institutions.

The Bacterial Flora of the Soil.—Unfortunately for ease of identification, bacteria change their appearance so easily with slight variations in conditions, and many of them can effect so wide a range of chemical reactions, that it is difficult to characterise them exactly. The individual species have, therefore, not been fully catalogued. Conn[2] found that about 5 to 10 per cent. of the colonies on gelatine plates consisted of large spore-forming bacteria related to *Bacillus subtilis;* about 10 per cent. were non-sporing organisms related to *Pseudomonas fluorescens*, rapidly liquefying gelatine; while 40 to 75 per cent. were short non-sporing rods with much less, if any, power of liquefying gelatine.

Several methods of classification have, however, been adopted since the crude physiological method (p. 413) was discarded.

Organisms studied in pure culture are grouped (*a*) morphologically and (*b*) physiologically. They fall into two divisions according to the material from which they derive their energy :—

(1) *Autotrophic forms* which can live partly or wholly without organic matter : the small but remarkable group which obtain energy by the oxidation of inorganic substances such as ammonia, nitrite, sulphur, hydrogen, and ferrous compounds.

[1] H. Krzemieniewski and S. Krzemieniewski, *Acta Soc. Bot. Polon.*, 1927-1928, **5**, p. (46).

[2] *J. Bact.*, 1917, **2**, 35.

(2) *Heterotrophic forms:* the numerous varieties that require organic sources of energy.

Only a small fraction of the total bacterial flora has been studied in pure culture, however; for the great mass of the population other methods are used. Conn divided them up morphologically into :—

(*a*) The large spore formers such as *B. megatherium*, *mycoides*, and others, conspicuous on the plates and therefore at first thought to be important but, as their numbers show little or no change with changing conditions, he assumes them to be inert ; [1]

(*b*) The small non-spore formers which, being more abundant and more variable with the conditions, are assumed to be active. Many of them grow only slowly on artificial media and are therefore difficult to isolate.

Winogradsky adopts a different method. By his staining technique he distinguishes :—

(*a*) An *autochthonous group*, present in the natural unmanured soil however poor, consisting largely of short rods and cocci in small clumps.

(*b*) A *zymogenic group* which comes into sudden prominence when a source of energy is added to the soil but dies down again as soon as this is exhausted. The particular numbers developing depend on the conditions (p. 353).

While we are not in a position to describe the soil bacteria in any detail there seems little doubt that they are not a fortuitous assemblage of all the possible forms, but represent a definite central flora, with, however, an admixture of stray and casual organisms.

The common soil bacteria seem to be the same all the world over so far as it is possible to judge ; any identifiable organism common in one place usually occurs in any other region where it is sought. Only two or three forms show clear signs of localised geographical distribution, *viz.*:—

[1] M. Tyagny-Ryadno (*J. Agric. Sci.*, 1933, **23**, 335) has attributed to *B. mycoides* an active rôle in rendering phosphates soluble in the soil.

(1) Certain of the nodule organisms, such as those associated with lucerne, soy bean, crotalaria, etc., which seem to be confined in their distribution to the districts occupied by the host plant.

(2) Certain of the phenol-decomposing organisms.[1]

From time to time local forms of widely distributed organisms have been described, *e.g.* the Nitrosomonas found by Omeliansky in Java, and *Azotobacter Vinelandii* found by J. G. Lipman in New Jersey, but whether these are truly local or simply rare forms that might be found elsewhere with systematic search, or stages in a complex cycle, is not known. Nor is it known whether, as happens with algæ and protozoa, the number of species increases as the conditions become more favourable to micro-organic life.

Some, if not all, of the bacteria pass through a complex life cycle in the soil (pp. 357, 392 and 462).

A group of filterable organisms has recently been found in sewage which may have come from the soil as they do not occur in tap water or in fæcal matter. Their diameter varies from 0·2 μ to 0·5 μ : they grow best in media of *p*H about 8 and cease growth at *p*H 7.[2]

The Number of Bacteria in the Soil.—The earlier investigation of bacterial numbers in soils was carried out by means of the plating technique. A suspension of the soil was diluted to a known gelatine medium, the colonies formed were counted and the figures multiplied by the dilution to give the number of these particular bacteria per gram. The method fails to estimate the total bacterial content of the soil because no plating medium permits all groups of soil bacteria to develop and form colonies. It is, however, very useful for identifying the organisms and it has been carefully standardised, both in regard to the medium employed and to the sampling

[1] P. H. H. Gray and H. G. Thornton, *Zbl. Bakt.*, Abt. II, 1928, **73**, 74.

[2] P. P. Laidlaw and W. J. Elford, *Proc. Roy. Soc.*, 1936, B, **120**, 292.

technique.[1] Plating methods usually give numbers ranging from about 5,000,000 to about 40,000,000 per gram in field soils.

Direct counts under the microscope were made by Conn [2] using a modification of the milk method; the numbers averaged about 260,000,000 per gram. Winogradsky developed a different method by means of which Kühlmorgen-Hille [3] obtained figures averaging 326,000,000 per gram. A third method developed by Vande Velde and Verbelen [4] gave counts ranging from 1,280,000,000 to 2,160,000,000. The main difficulty in estimating numbers by the direct method is that of measuring the small amount of soil examined. Gray and Thornton overcame this by adding a counted suspension of indigo particles to the soil and then determining the ratio of bacteria to indigo particles in stained films of this suspension.[5] This method was tested by adding a counted suspension of bacteria to sterilised soil and then counting the numbers found: the agreement was satisfactory.

The bacterial numbers found by this method are many times higher than those given by the plate method: the results for three soils from Barnfield arable and Park grassland are shown in Table 78.

The total cell count from the arable soil is 117 to 133 times as great as the plate count, the ratio being fairly constant for the three plots. For the grass plots the total cell counts are much the same but the plate counts are very low, particularly for the two more acid plots. This is the usual result for acid soils; it is probably due to the failure of acidophilous groups to develop on the plating medium, which devised for bacteria that thrive in neutral conditions.

[1] H. G. Thornton, *Ann. Appl. Biol.*, 1922, **9**, 241; R. A. Fisher, H. G. Thornton, and W. A. Mackenzie, *ibid.*, 1922, **9**, 325.

[2] H. J. Conn, *N.Y. St. Agric. Expt. Sta. Tech. Bull.* No. 64, 1918.

[3] G. Kühlmorgen-Hille, *Zbl. Bakt.*, Abt. II, 1928, **74**, 497.

[4] A. J. J. Vande Velde and A. Verbelen, *C.R.*, 1930, **190**, 977.

[5] P. H. H. Gray and H. G. Thornton, *Nature*, 1928, **122**, 400.

TABLE 78.—BACTERIAL NUMBERS IN ROTHAMSTED FIELD SOILS. H. G. THORNTON.

Manuring.	pH.	Numbers per Gram.		Ratio: Total Count to Plate Count.
		Total Cell Count. (Direct Method.)	Plate Count.	
Plot. *Barnfield.* (*Arable, Mangolds*)				
1-O Farmyard manure	7·6	3,733,000,000	28,860,000	129
4-A Complete minerals + ammonium sulphate .	7·2	1,766,000,000	15,100,000	117
8-O No manure .	8·0	1,005,000,000	7,550,000	133
Park Grass Plots.				
13 Farmyard manure	4·6	2,395,000,000	2,250,000	1064
11-1 Complete minerals + ammonium sulphate .	3·8	2,403,000,000	1,350,000	1780
12 No manure .	5·6	3,041,000,000	7,500,000	405

The " total cell counts " include recently dead, as well as living, bacteria, but since the enzymes of a bacterial cell can probably continue to act after the cell has lost its power of multiplication, the total cell count is still valuable for relating bacterial numbers with biochemical activity.

The numbers of bacteria in the groups counted do not remain constant in field soils, but are subject to large changes, which are of at least two types. There is a seasonal change, the general level of numbers being highest in spring and autumn [1] (Fig. 46). Superimposed on the seasonal changes are fluctuations at short intervals. Cutler and his colleagues found large daily fluctuation in samples taken from the same field. Thornton and Gray, and more recently Taylor,[2] have shown that fluctuations take place even at intervals of a few hours. Different groups of bacteria rise and fall at different

[1] D. W. Cutler, L. M. Crump, and H. Sandon, *Phil. Trans. Roy. Soc.*, 1922, B, **211**, 317.

[2] H. G. Thornton and P. H. H. Gray, *Proc. Roy. Soc.*, 1930, B, **106**, 399; H. G. Thornton and C. B. Taylor, *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 175; C. B. Taylor, *Proc. Roy. Soc.*, 1936, B, **119**, 269.

times [1] as shown by the difference between plate counts and direct (microscope) counts (Fig. 47), but the groups counted,

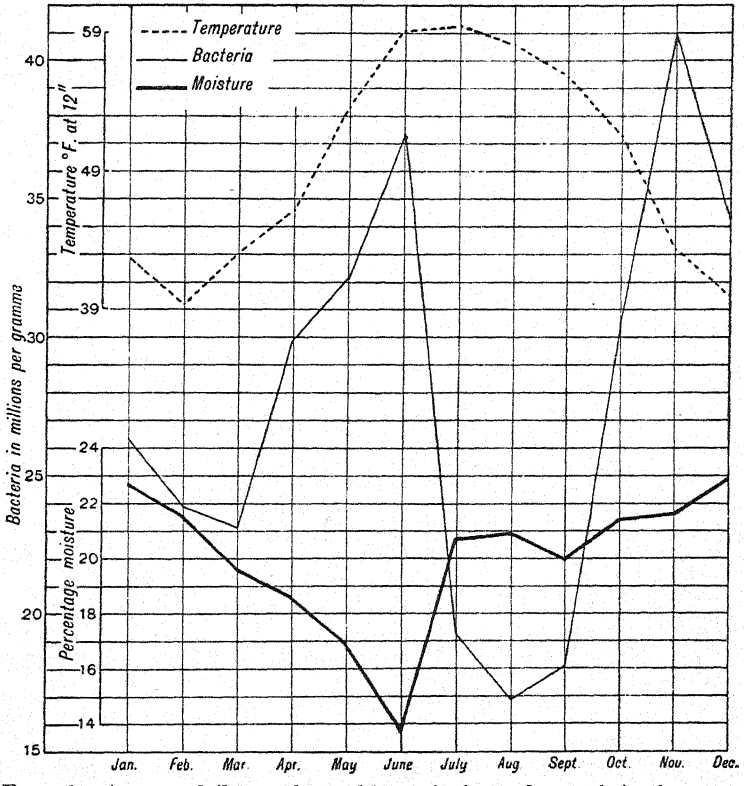


FIG. 46.—Average daily numbers of bacteria for each month in the year, 5th July, 1920, to 4th July, 1921 (as determined by the plating method), together with average daily percentage moisture, and temperature at 12-inch depth, in soil. (Cutler and Crump, *Problems in Soil Microbiology*, p. 16.)

taken as a whole, usually rose to high numbers about 10 a.m., fell towards midday, and rose again in the afternoon.

[1] N. R. Smith and S. Worden (*J. Agric. Res.*, 1925, **31**, 501) claim that their medium, which gave higher numbers than Thornton's, showed no fluctuations. If this were correct, it might mean that some fluctuations cancelled out others. H. G. Thornton and R. A. Fisher showed, however (*Soil Sci.*, 1927, **23**, 253) that Smith and Worden's data indicate significant fluctuations.

The protozoan population of the soil shows similar changes, but owing to technical difficulties, protozoal fluctuations can-

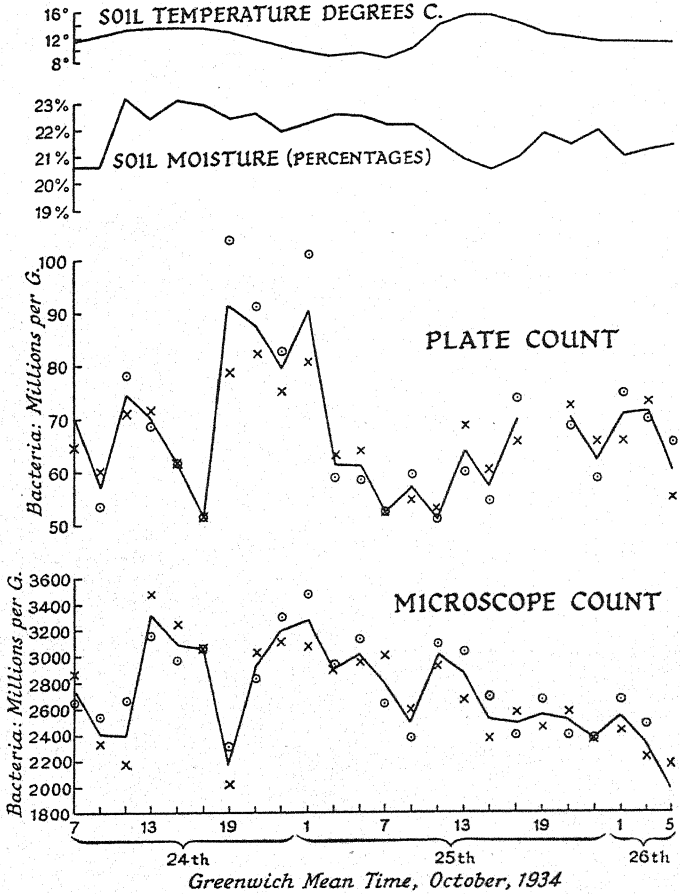


FIG. 47.—Microscope and plate counts of bacteria from two-hourly samples of fallow garden plot soil.

Note.—In the curves shown here, the dots and crosses represent numbers found in duplicate samples; all curves show mean values (H. G. Thornton and C. B. Taylor, *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, I, 175).

not be measured at shorter than daily intervals. The daily fluctuations in bacterial numbers observed by Cutler, Crump,

and Sandon were inversely related to the numbers of active amœbæ in the soil, thus differing from the seasonal changes.

The soil bacteria constitute a significant fraction of the soil organic matter. The average size of a bacterium is approximately that of a cube 1/1000 mm. side: 1,000,000,000 will therefore occupy about 1 cub. mm., weigh about 1 mg., and occupy about one-thousandth part of the soil volume; 5,000,000,000 per gram is not an uncommon number for a manured soil: this corresponds to 7500 lb. bacterial substance per acre, containing about 1500 lb. dry matter and 150 lb. nitrogen. In soil freshly manured, or treated with straw or green manure, the numbers may temporarily and locally become much greater.

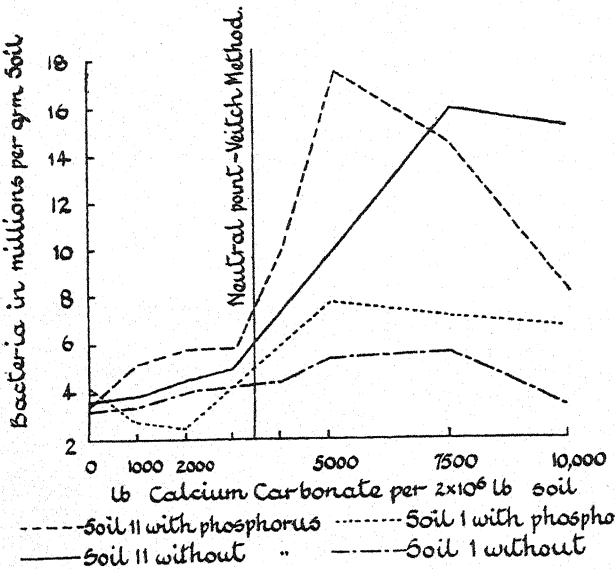
Effect of External Conditions on Bacterial Numbers.—The existence of these fluctuations makes it very difficult to trace the effect of external conditions on the numbers of bacteria in the soil. Isolated counts are of little use; it is necessary to have sufficiently extensive data to justify the application of statistical methods.

The chief factor influencing bacterial numbers in the soil is the amount of energy material available, the numbers rapidly rising when the energy material increases. In podzol profiles the bacteria occur chiefly in the organic matter horizon: there is much less activity in the other layers.[1] There appears also to be a close connection between bacterial numbers and nutrient supplies, especially of nitrogen and phosphate, though this has been established more clearly for bacterial activity than for numbers.[2]

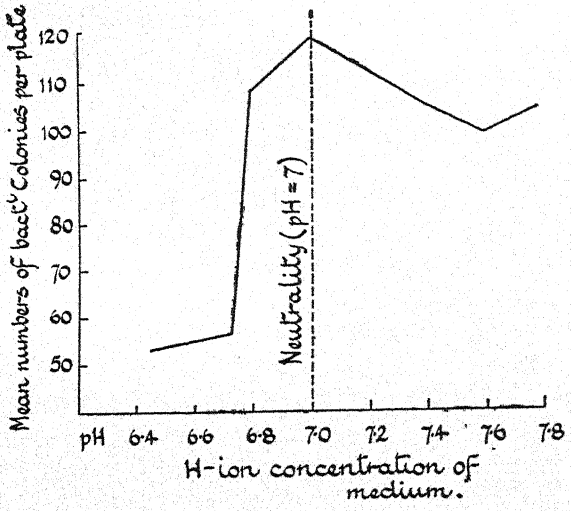
Certain soil bacteria are much affected by the reaction of the medium. This has already been shown in Table 77 (p. 425). A further illustration is given in Fig. 48A, which shows the numbers of certain kinds present in an acid soil to portions of which calcium carbonate has been added. In the

[1] P. H. H. Gray and N. B. McMaster, *Canad. J. Res.*, 1933, 8, 375.

[2] For influence of energy supply see pp. 457-464; for nitrogen see pp. 385, 434, 472; for potassium see J. Dumont, *C.R.*, 1897, **125**, 469.



A. Effect of successive additions of calcium carbonate to an acid soil on numbers of bacteria developing on a specified medium (F. E. Bear, *Soil Sci.*, 1917, 4, 433).



B. Effect of change in reaction of an agar medium (H. G. Thornton, *Ann. Appl. Biol.*, 1922, 9, 241).

FIG. 48.—The effect of reaction on numbers of bacteria.
A : in soil ; B : in agar medium.

original soil the numbers are low. Additions of small amounts of calcium carbonate have but little effect, nor have larger ones till the soil is neutral according to the Veitch method; then a marked rise occurs. Further additions of calcium carbonate, however, cause a gradual fall; both rise and fall are intensified when phosphate is added. Similar results were obtained by Fabricius and von Feilitzen;[1] 0·1 million bacteria occurred per gram in raw moorland soil, but 7 million per gram in adjoining soil that had been cultivated and manured.[2]

These results are compared in Fig. 48 B with those Thornton obtained by plating a soil suspension on agar media of different reactions: the numbers are small for low *p*H values: they rise suddenly between *p*H 6·8 and 7·0, and gradually fall at higher values.

The different kinds of bacteria are not equally affected, however, by the changes in *p*H. The nitrogen-fixing organisms (*Azotobacter* and some varieties of *B. radicicola*) show the sharpest response, occurring in quantity only under a narrow reaction range: nitrifying organisms are very susceptible, some of the other organisms are less affected. Table 78 shows that the total numbers of bacteria revealed by direct counts altered but little for wide variations in *p*H value, though the numbers developing on plates altered considerably.

The soil bacteria are somewhat unresponsive to changes in temperature or moisture supply within the limits favourable to trophic life. The hourly fluctuations in numbers showed no relation to temperature or moisture content. Fig. 46 suggests a direct relation between bacterial numbers and soil temperature at Rothamsted during spring and up till June, but an inverse relation in autumn; but it is impossible to separate out the effect of the spring and autumn maxima already mentioned. Fehér[3] at Sopron also found that the fluctuations in

[1] *Zbl. Bakt.*, Abt. II, 1905, **45**, 161.

[2] See also Th. Arnd, *Zbl. Bakt.*, Abt. II, 1916, **45**, 554.

[3] D. Fehér, *Arch. Mikrobiol.*, 1933, **4**, 447.

number varied with temperature, but that at a given temperature they were governed by the water supply. In their detailed analyses of the plate counts of daily samples from Barnfield, Cutler and Crump [1] concluded that increased temperature tended to lower the numbers, while increased moisture content tended to raise them. This accords with observations in Russia: in the cool northern and moister regions the bacteria concentrate about 10-15 cm. below the surface of the soil, while in the drier regions they extend much more deeply: it is even claimed that in some Turkestan soils the maximum numbers of *Azotobacter* occur at 5 m. or more below the surface.[2]

In partially sterilised soils, on the other hand, where the population of micro-organisms is simplified, the numbers of bacteria increase to the maximum as the temperature and moisture rise. This accords with the earlier results of Russell and Hutchinson on soils kept under constant controlled conditions (Table 79). It will be shown later (p. 462) that fluctuations

TABLE 79.—EFFECT OF TEMPERATURE OF STORAGE ON BACTERIAL NUMBERS IN SOILS, MILLIONS PER GRAM. RUSSELL AND HUTCHINSON, 1913.

Temperature of Storage °C.	Untreated Soil.				Soil Treated with Toluene.			
	At Start.	After 13 Days.	After 25 Days.	After 70 Days.	At Start.	After 13 Days.	After 25 Days.	After 70 Days.
5°-12°	65	63	41	32	8·5	73	101	137
20°	65	41	22	23	8·5	187	128	182
30°	65	27	50	16	8·5	197	145	51
40°	65	14	9	33	8·5	148	52	100

of considerable magnitude can occur even under constant conditions of temperature and moisture content.

But when the soil is exposed to temperatures outside the

[1] *Problems in Soil Microbiology*, Rothamsted Monographs: Longmans, Green & Co., 1936.

[2] D. A. Sabinin and E. G. Minina, *Proc. 2nd Int. Cong. Soil Sci.*, Moscow, 1932, **3**, 224.

limits of trophic life, some remarkable results appear. Conn [1] showed that freezing the soil, so far from depressing bacterial numbers, greatly increased them; the numbers of bacteria in frozen soils kept at — 12° C. were considerably higher than at ordinary temperatures,[2] a result that has never been adequately explained. Exposure to temperature above the normal causes, as one might expect, a drop in the numbers of organisms; but if the temperature has risen above a certain critical value (about 45° C.) this drop is followed by a considerable and permanent rise in numbers when the soil regains its normal temperature (p. 476).

Similar effects are produced by extreme changes in the moisture content of soils. Drying the soil in air at first lowers the bacterial numbers, but on re-wetting they may rise considerably, though not for long. Waterlogging, however, alters the flora.

These curious facts are discussed on pages 405, 476.

The soil bacteria participate in most of the chemical changes going on in the soil, but there is no clear relation between the rate of evolution of CO_2 and the numbers of bacteria such as is found for sand mixed with sugar and inoculated with a little soil.[3]

There are important differences between bacteria and fungi as decomposing agents in the soil. Fungi reassimilate 20 to 60 per cent. (more usually 30 to 40 per cent.) of the carbon of the substratum they have decomposed, while bacteria reassimilate much less, only 1 to 30 per cent., usually 5 to 10 per cent.[4] But for one part of carbon assimilated, bacteria

[1] *Zbl. Bakt.*, Abt. II, 1910, **28**, 422; 1914, **42**, 510.

[2] Confirmed by P. E. Brown and R. E. Smith at Iowa (*Iowa Agric. Expt. Sta. Res. Bull.* No. 4, 1912), but not by A. Wojtkiewicz, *Zbl. Bakt.*, Abt. II, 1914, **42**, 254-261, who obtained low numbers in winter and no high ones till spring. A. G. Lochhead found a slight rise in numbers in frozen Canadian soils but a much bigger rise on thawing. See also A. F. Vass, *Cornell Agric. Expt. Sta.*, Mem. No. 27, 1919.

[3] Cutler and Crump, *Problems in Soil Microbiology*, p. 35.

[4] S. A. Waksman, *J. Agric. Sci.*, 1924, **14**, 555; W. Kruse, *Allgemeine Mikrobiologie*, Leipzig, 1910.

assimilate considerably more nitrogen than do fungi, containing in their dry substances 10 to 12 per cent. of nitrogen against 5 to 8 per cent. in the dry matter of fungi.

Bacteriophage.—N. L. Söhngen [1] has isolated from soil certain organisms capable of producing a bacteriophage that dissolves living bacteria : he also found a similar substance in the soil. It has been studied by Demolon and Dunez in relation to lucerne sickness (p. 399).

Soil Protozoa.

The suggestion that protozoa form a normal part of the soil population influencing the growth of plants was made by Russell and Hutchinson as the result of the investigations on partial sterilisation of the soil.

Protozoa had been found in the soil, and the earlier workers, Ehrenberg and Dujardin (1841) thought of them as active, but, after the discovery of cyst forms by Stein in 1878, the idea grew up that they occurred in soil only accidentally and as cysts.

C. H. Martin and K. R. Lewin [2] were the first to develop a direct method of detecting protozoa in the soil : they did it by stirring soil into a solution of picric acid and then picking up the organisms floating on the surface. The method is tedious and not very effective ; it was, however, improved by M. Koffman,[3] who made soil into a thin paste with water, stirred vigorously, drew off the supernatant liquid and examined it. Direct microscopic examination of the soil reveals little or nothing, a fact that caused considerable difficulty in accepting the idea of a protozoan fauna till Cutler found the explanation.[4] He showed that the organisms rigidly adhere to the soil particles, and indeed up to a certain limit they can

[1] *K. Acad. Wet.*, Amsterdam, 1923, **36**, 1281. See also J. Bordet, *Proc. Roy. Soc.*, 1930, B, **107**, 398.

[2] *Phil. Trans. Roy. Soc.*, 1914, B, **205**, 77.

[3] *Medd.* 391, *CentAnst. Försöksv., Bakt. Avdel.* Nr. 55, 1931.

[4] *J. Agric. Sci.*, 1920, **10**, 135.

be completely removed from a suspension by shaking for a few minutes with soil. The saturation capacity of the soil is high; at Rothamsted it is 1,500,000 or 2,000,000 protozoa per gram, a figure considerably in excess of the numbers present. Only in exceptional cases can organisms be dislodged sufficiently readily to be recognised under the microscope. The phenomenon is discussed more fully on page 470.

Surveys of soils from other countries have shown [1] that there is a central group of protozoa, of almost universal occurrence, forming a soil fauna, which, like the flora of bacteria and algæ, persists all over the world with remarkably little variation; Sandon's examinations ranged from Gough Island, in the Antarctic, to Spitzbergen in the Arctic regions. The predominant members of this soil fauna are:—

Amœbæ.—Nægleria (*Dimastigamœba*) *gruberi*,[2] *Hartmanella hyalina* (one or other, but not both together).

Flagellates.—Heteromita lens and *globosa*, *Cercomonas crassicauda*, *Oicomonas termo*.

Ciliates.—Colpoda cucullus and *steinii*.

In addition, there are generally some shelled amœbæ (*Thœcamœbæ*), among them *Chlamydophrys stercorea*, *Difflugia constricta* and *Trinema enchalys*.

Sandon gives a classification and a key to all recorded species of soil protozoa in his Monograph (1927).[3]

It is not yet possible to explain why certain forms should be so widespread in the soil, and others, not apparently very different, should be so rare. It is, perhaps, significant that all the common soil forms are small; the amœbæ range from 8 to 22 μ diameter, the flagellates from 7 to 15 μ and the

[1] H. Sandon, *The Composition and Distribution of the Protozoan Fauna of the Soil*, Oliver & Boyd, 1927.

[2] This form is called *Vahlkampfia soli* in Martin and Lewin's paper (1914).

[3] For other investigations see L. de Telegdy-Kováts, *Kisérl. Kozlem.*, 1928, **31**, 3; D. Fehér and L. Varga, *Zbl. Bakt.*, Abt. II, 1929, **77**, 524; A. Lwoff, *Recherches biochimiques sur la nutrition des Protozoaires: le pouvoir de synthèse. Monographie de l'Institut Pasteur:* Masson, Paris, 1932; L. Varga, *Ann. Inst. Pasteur*, 1936, **56**, 101.

Thœcamœbæ about 15 μ. There are few, if any, of the larger forms, such as occur with some of the soil species in other habitats, *e.g.* in stagnant water. The wide persistence of the soil forms is all the more remarkable in view of the fact, that, apart from the *Thœcamœbæ*, which are relatively insignificant in numbers, the various members of the population are simply masses of naked protoplasm having no protection against heat, cold, or drought, nor can they get away from adverse conditions by sinking to lower depths as can the plankton in the sea. Their property of forming cysts, apparently as part of their normal life cycle,[1] enables a proportion of them to survive periods when otherwise they might die.

The organisms go through a cycle of changes in the soil; some of the flagellates have an amœboid stage, and at least one of the amœbæ (*Nægleria*) has a flagellated stage.

There is no evidence of geographical distribution nor of clear-cut ecological associations of protozoa corresponding with those of plants. There are, however, certain distributions which cannot yet be explained; but two common amœbæ, *Nægleria* (*Dimastigamœba*) and *Hartmanella*, appear to be mutually exclusive and rarely occur together in any quantity; one or other dominates, but not both. The number of varieties is usually highest in those soils containing the greatest numbers of individual protozoa.

The flagellates are the most numerous, the amœbæ come next, and the ciliates are by far the fewest (Table 81, p. 456).

The organisms are not all active at any one time; the proportion of active forms varies considerably, but on most days they constitute more than half of the total numbers.

The numbers of protozoa in the soil, however, do not remain even approximately constant, but change continuously from day to day. This is particularly true of the individual species; it is not uncommon for the numbers of any one species to vary from a few hundreds to 400,000 or more within twenty-four

[1] D. W. Cutler and L. M. Crump, *Problems in Soil Microbiology*, 1935, p. 67.

hours; moreover, in the same period the percentage of individuals found in the active form may jump from 0 to 100.

Two kinds of change occur :—

(1) A definite two-day periodicity is shown by the active *Oicomonas termo* (Fig. 49), the numbers being high one day and low the next.

(2) A continuous fluctuation shown by the amœbæ, which,

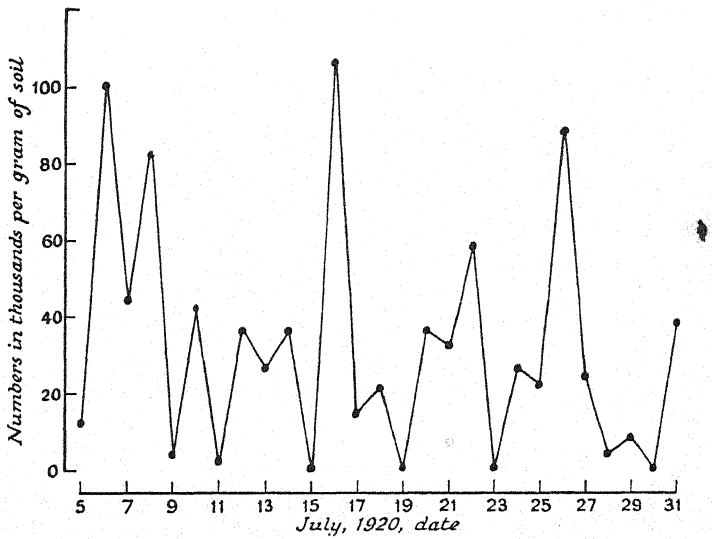


FIG. 49.—Daily counts of an active flagellate (*Oicomonas termo*) in Barnfield, Plot 2 (dunged), (Cutler, Crump, and Sandon). The numbers are in thousands per gram, and show a remarkable periodicity.

if it be a periodicity, does not correspond with our days (Fig. 50).

These fluctuations make it difficult to study the effect of external conditions on the protozoan fauna, only two or three factors being sufficiently potent to over-ride them. Of these, the most important are :—

The amount of organic matter (*i.e.* energy material) in the soil; as this increases there is an increase in the bacterial numbers and therefore in the general level of numbers of individual protozoa and also in the number of varieties.

The effect of season is also marked, the numbers of all forms being higher in spring and autumn than in summer and winter.

Aeration probably has a potent influence in determining the numbers of organisms, but other external conditions have little effect on protozoan numbers. The amœbæ are much

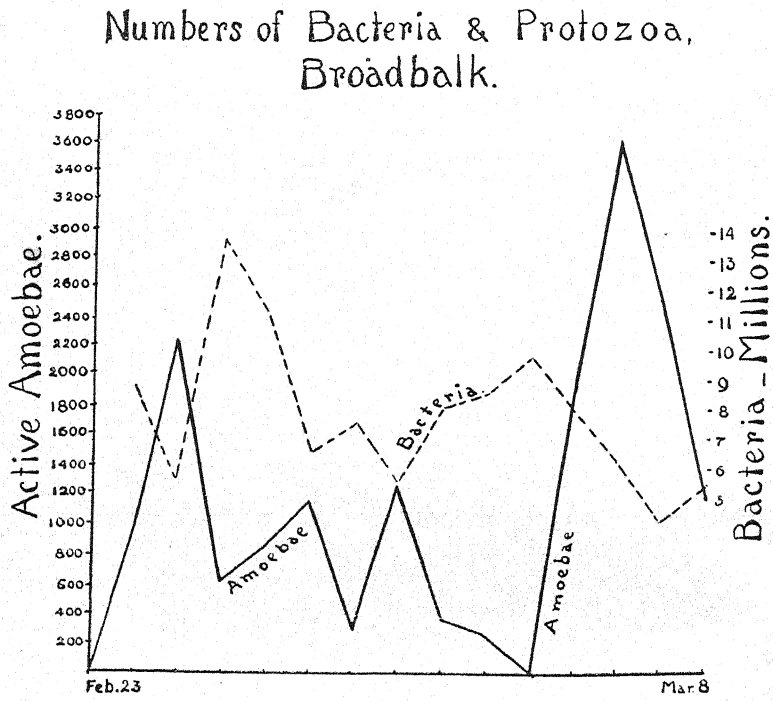


FIG. 50.—Daily counts of active amœbæ and of bacteria (plate counts) in Broadbalk, Plot 2 (dunged), (Cutler and Crump). The active amœbæ are given in thousands, and the bacteria in millions, per gram of soil.

less common in alkaline than in peaty or acid soils: one or two forms are checked when acidity exceeds *p*H 6, but in the main the protozoa are very tolerant of variations in acidity. Increased temperature tend to reduce the numbers of some (*e.g. Nægleria*) but not others (*e.g. Heteromita*) in the soil, but

variations in moisture content and in rainfall had no marked effect.[1]

The relationships of the ciliates and amœbæ to the other members of the soil population are under investigation at Rothamsted. Both groups of protozoa feed on bacteria so that the forms active in the soil are detrimental to bacteria and keep down their numbers. The numbers of active amœbæ are inversely related to those of bacteria as counted by the plating method; when the amœbæ increase, the bacteria decrease, and conversely.[2]

The different bacteria have widely different values as food for amœbæ: for one of the most nutritious, an increase of 3400 amœbæ (*Hartmanella hyalina*) involved the disappearance of 1·4 million bacteria; *i.e.* something over 400 bacteria were consumed to produce one amœba. Translating these figures into terms of the amœbal increases shown in Fig. 49, the bacterial population of 1 to 5 thousand million per gram is about sufficient to keep the protozoa active.[3]

Some of the flagellates resemble amœbæ in feeding on bacteria and their relationships to soil bacteria are, therefore, presumably very similar. But others are different. They feed on soluble organic and inorganic substances, which they absorb by diffusion through their body surface, *i.e.* they feed saprophytically;[4] their relation to plant growth is not known.

From the circumstance that active amœbæ reduce the numbers of bacteria in the soil it was at first supposed that their action was entirely detrimental to soil fertility. This is now known to be incorrect. The individual organisms in the

[1] *Problems in Soil Microbiology*, 1935, p. 75.

[2] C. B. Taylor observed a similar relationship counting the bacteria by the ratio method (*Proc. Roy. Soc.*, 1936, B, **119**, 269).

[3] See p. 434, and D. W. Cutler and L. M. Crump, *Brit. J. Expt. Biol.*, 1927, **5**, 155; see also L. B. Severtzova, *Zbl. Bakt.*, Abt. II, 1928, **73**, 162, who draws up a list of "acceptable" and "non-acceptable" organisms, and finds that amœbæ prefer small bacteria but take large cocci in preference to vegetative forms of spore formers.

[4] H. G. Thornton and Geoffrey Smith, *Proc. Roy. Soc.*, 1914, B, **88**, 151.

smaller population are more efficient than those in the larger population and the total amount of plant food produced is not in simple proportion to their numbers (p. 465).

Worms.

Nematodes.—The nematodes are small worms of about 0·5 mm. to 1·5 mm. in length and about one-twentieth mm. to one-fortieth mm. across : many genera and species are regular soil inhabitants.

The soil forms fall roughly into three groups :—

(1) Those living on decaying organic matter and possibly on bacteria, protozoa, and fungi : these are the most numerous and many different forms of them occur in the soil.

(2) Those parasitic on plants : including species of Aphelenchoides, Anguillulina, Tylenchus, and Heterodera.

(3) Those predatory on other nematodes, rotifers and small earthworms : these include Mononchs and some Diplogasters.

The classification of nematodes has been studied by de Man[1] and by Micoletzky.[2] The free-living forms in the main feed on juices which they pump in by means of a muscular œsophagus. The parasitic forms have been much studied because of their technical importance. T. Goodey has recently summarised existing knowledge of them in a useful volume.[3]

The predatory forms were studied by Cobb,[4] who showed much ingenuity in overcoming the practical difficulties of investigating the nematode population of the soil.

Nematodes occur in largest numbers on soils well provided with organic matter, and they are more numerous in summer than in winter : estimates of their number are rough and

[1] J. G. de Man, *Die frei in der reinen Erde und im süssen Wasser lebenden Nematoden*, Leiden, 1884.

[2] H. Micoletzky, *Arch. Naturgesch.*, 1921, A, **87**, 1.

[3] T. Goodey, *Plant Parasitic Nematodes and the Diseases they Cause*, Methuen, London, 1933.

[4] N. A. Cobb, *U.S. Dept. Agric. Yearbook*, 1914, 457 ; *Soil Sci.*, 1917, **3**, 431.

uncertain but the values range about 0·1 to 4·5 per grm. of soil:—

	Per Gram.	Per Acre, Millions.
Maize field, Missouri, U.S.A.[1]	0·11-0·76	100-650
Sugar-beet fields, Utah, U.S.A.:[2]		
Field 1 . . .	0·87	785
Field 2 . . .	1·22	1114
Aberdeen soils:[3] Winter .	2·4	2200
Summer .	4·4	4300

Of the various forms the free-living are probably the most numerous.

Many nematodes can resist drought by passing into a quiescent stage. Their influence on soil fertility is not yet known. The parasitic forms do much damage, especially in temperate regions, to oats, clover, lucerne, sugar beet, potatoes: and, in glasshouses, to tomatoes and cucumbers: besides doing direct injury they may aid in the spread of fungal and bacterial diseases or pests.

The saprophagous forms assist in the disintegration of plants and organic residues, and the predatory forms possibly serve a useful purpose in keeping parasitic forms within bounds. Attempts have been made from time to time to control the parasitic forms by inoculating infested soil with predatory forms but so far without success.

There has been much discussion as to how the parasitic forms find their host plants in the soil. There is good evidence that root exudations attract them, and that their chemotactic sense is fine enough to enable them to distinguish one kind of plant from another.

[1] G. Steiner and H. Heinly, *J. Wash. Acad. Sci.*, 1922, **12**, 367.

[2] G. Thorne, *J. Agric. Res.*, 1927, **34**, 265.

[3] D. Robertson, *Proc. Roy. Phys. Soc.*, Edin., 1926, **21**, 83. The numbers are quoted in "billions" per acre. Dr. Rennie informed me that the word is used in its American sense of one thousand million, not in the English sense of one million million.

The subject is discussed in detail by Steiner [1] who suggests that the receptive organs are the amphids or lateral organs located in the head. Rensch [2] showed that these parasitic forms can be made to accept not only the natural root exudations but artificial preparations, and he proposed a treatment of affected soil by this method, in the hope that the organisms thus brought out, finding no host plant, would die. So far no practical result has yet been achieved, but this line of investigation is being pursued at the Institute of Agricultural Parasitology, St. Albans, in attempts to control the race of *Heterodera* now attacking potatoes in this country, and doing in some areas great damage.

The Remaining Invertebrate Fauna of the Soil.

Quantitative faunistic studies of the invertebrates other than protozoa have been made at Rothamsted by Morris,[3] Ladell [4] and K. D. Baweja, and in Cheshire by Cameron.[5] Ladell separated the fauna by stirring the soil by means of a stream of fine air bubbles in a solution of magnesium sulphate of about 1·11 specific gravity. The animals are brought to the surface and floated over a sedimentation tank and then on to a filter paper: they are then counted and identified. This method shows that many more animals are present than was previously supposed.

The fauna includes many species. Some are only temporary inhabitants, using the soil as a convenient place for breeding or pupation; indeed a large number of known species of insects pass some stage of their life in the soil. The

[1] *Phytopath.*, 1925, **15**, 499.

[2] *Ztschr. Wiss. Zool.*, 1924, 113; *Mitt. Deut. landw. Ges.*, 1924, **39**, 412.

[3] H. M. Morris, *Ann. Appl. Biol.*, 1920, **7**, 141; 1922, **9**, 282, and 1927, **14**, 442.

[4] W. R. S. Ladell, *ibid.*, 1936, **23**, 862.

[5] A. E. Cameron, *J. Econ. Biol.*, 1913, **8**, 159, and *Trans. Roy. Soc.*, Edin., 1917, **52**, 37. For other work see P. Buckle, *J. Ecol.*, 1923, **11**, 93; M. Thompson, *Ann. Appl. Biol.*, 1924, **11**, 349; J. F. von Pfetten, *Ztschr. Angew. Ent.*, 1925, **11**, 35; E. E. Edwards (Aberystwyth survey: arable land), *Ann. Appl. Biol.*, 1929, **16**, 299.

permanent inhabitants include phytophagous forms feeding on plants, predaceous forms feeding on other animals, and saprophagous forms feeding on organic matter (Table 80). The

TABLE 80.—NUMBERS OF SMALL ANIMALS (MILLIONS PER ACRE) TO A DEPTH OF 9 INCHES FOUND IN SOIL AT ROTHAMSTED (1936). K. D. BAWEJA, USING W. R. S. LADELL'S APPARATUS.

	Broadbalk (Continuous Wheat).		Grass Land.[1]
	Manured.	Unmanured.	
Insects	57·85	41·0	56·25
Nematodes, etc.	1·85	0·33	4·87
Myriapods :			
Millipedes	3·57	1·00	0·37
Centipedes	0·22	0·25	0·13
Others	0·14	0·58	1·25
Earthworms	2·75	0·50	8·62
Arachnids :			
Mites	7·72	3·00	3·13
Spiders	—	0·08	—
Woodlice	0·28	0·25	—
Molluscs	0·07	—	—
Total	74·45	47·0	74·62
Period of Observation	February to July, 1936		April to July, 1936

most numerous are the insects, but the most important as soil-makers are worms of various kinds, including Enchytraeids,[2] oligochaetes and particularly the earthworms.

The effect of organic matter, especially farmyard manure, in increasing the numbers of all forms is usually very marked, as seen in Table 80. An extreme case was observed on meadow land near Oxford, covered by a thick mass of vegetation and rotting grass, where Ford [3] found the density of population of small animals on the ridges to a depth of 9 inches to be over 263 millions per acre of which 90 per cent. were Springtails (*Collembola*).

[1] The grassland figures do not include the months of February and March when the soil populations seem to be high. The figures are, nevertheless, as great as those of the heavily manured arable land.

[2] G. Jegen, *Landw. Jahrb. Schweiz.*, 1920, **34**, 55.

[3] J. Ford, *J. Animal Ecol.*, 1935, **4**, 195.

Unlike the micro-organisms, the invertebrates show very marked response to geographical factors so that there is a well-marked geographical distribution. Within the geographical regions there are, no doubt, ecological communities, but these have hardly been studied as yet.

Earthworms.—The earthworms have been studied in detail as a result of the classical investigation by Darwin described in *Earthworms and Vegetable Mould*, one of the most interesting books on soil ever written. Earthworms produce two important effects in the soil; aerating it and mixing its constituents; they pass large quantities of material through their bodies and eject it on the surface as "worm casts," which Darwin estimated would form a layer 0·2 inch thick in the course of a year. They are thus perpetually turning the soil over to the depth to which they operate, mingling the various soil constituents, dragging in leaves and other plant residues from the surface, and thus facilitating decomposition by the micro-organisms. The results are very striking, and are well seen in comparing soils well stocked with earthworms with those containing only small numbers. Where earthworms are active in the soil, organic matter is distributed throughout the layer in which they operate. But where in cool climates earthworms are few or absent, there is much less mixing; the dead vegetable matter accumulates on the surface, becoming a partly decomposed, acid, peaty mass, in which the normal soil decompositions are not completed. The surface vegetation becomes profoundly modified, only few plants being able to force their way through the mass of dead material; as they die their remains also lie on the surface, and may, if the rate of decomposition be sufficiently slow, accumulate to form a bed of peat.

The second great effect of earthworms is to facilitate aeration and drainage. They honeycomb the soil with their burrows, leaving channels along which air and water easily pass.

A third action, formerly attributed to earthworms, but on

insufficient grounds, is that they increase the amount of decomposition of organic matter in the soil. No evidence for this could be found by the writer or by Heymons ;[1] grass cuttings mixed with the soil decomposed as readily in the absence of earthworms as in their presence. But in these experiments the aerating and mingling actions of the earthworms were excluded.

As happens with other organisms, the number of earthworms in a given weight of soil is governed by the amount of organic matter present. But earthworms are peculiarly sensitive to soil acidity and in their absence a mass of dead vegetation tends to accumulate on the surface of acid soils and changes into peat. The acid grass plots at Rothamsted contain only few earthworms,[2] although the adjoining nearly neutral plots contain many. Hanley records that the presence or absence of worm casts on pastures is one of the surest ways of showing whether the land is "sweet" or "sour." It is not certain whether the cause of the suppression of worms is a positive injury by acidity or a consequence of the calcium starvation from which everything growing on acid soils is liable to suffer [3] (p. 545).

One of the most difficult problems in the garden is to deal with the crude mixture of clay, sand, and small stones that often forms a considerable part of the soil. An effective method used by the writer with considerable success is to dig grass cuttings and other vegetable matter into the soil, burying much of it to a depth of about 8 inches, and to apply frequent dressings of grass cuttings and also of finely powdered calcium carbonate (chalk or limestone) to the surface.

[1] E. J. Russell, *J. Agric. Sci.*, 1910, **3**, 246 ; R. Heymons, *Ztschr. Pflanz. Düng.*, A, 1923, **2**, 97.

[2] They have also, perhaps consequently, no moles. Farmers in the north of England regard molehills as a good sign in grass land.

[3] Earthworms are largely dependent for their nutrition on calcareous glands which presumably cannot be maintained, and are liable to dissolution, in soil with much capacity for absorbing calcium. See also E. J. Salisbury, *J. Linn. Soc. Botany*, 1924, **46**, 415.

Earthworms multiply rapidly and wander from the upper to the lower layers of vegetable matter, thoroughly blending and aerating the soil.

Ants.—In hot dry climates ants and termites become as important in the soil as are the earthworms in the cool climates. They feed on organic matter but decompose it completely, leaving no residues for humus formation. They pile up the soil into heaps which sometimes are as much as 5 or 6 feet high. Some of them throw out from their burrows tiny mounds of fine earth which form an excellent bed for the growth of wild seedlings in contrast with the hot bare earth around; this may be a factor causing the patchy distribution of plants in these conditions.

Snails.—Atkins and Lebour have found that the numbers of snails in different districts are closely related to the reaction of the soil, being greatest when the *p*H is about 7.[1]

General Microbiology of the Soil.

The Soil Population.

The investigations recorded in the preceding pages show the invariable presence of organisms in the soil leading their lives there and bringing about changes of vital importance in soil fertility.

The groups of organisms present include algæ, fungi, actinomycetes, bacteria, protozoa, and larger forms. In spite of great differences among these organisms, they have certain properties in common in their lives in the soil, and they show certain relationships which appear to be of wide application.

For each of these organisms, there is a group occurring so commonly in a trophic form in the soil that it can be regarded as a definite soil flora or fauna. The whole of these groups make up the soil population.

So far as is known, the composition of the soil population

[1] W. R. G. Atkins and M. V. Lebour, *Sci. Proc. Roy. Dublin Soc.*, 1923, **17**, 233.

shows remarkably little variation in different parts of the world. The characteristic groups of algæ, bacteria, fungi, and protozoa are the same in the Arctic as in temperate and tropical climates; there are differences in the proportions of the various members of each group, but nothing corresponding with the geographical distribution of plant and animal groups. The reasons for this constancy of the soil population are to be sought, partly in the nature of the organisms themselves, partly in the soil as a habitat. It is possible, and indeed probable, that micro-organisms are less susceptible to environmental conditions than are the larger forms. It is certain that the biological conditions at a depth of from 2 to 7 or 8 inches below the soil surface vary much less than on the surface itself; the temperature is more even (p. 508), and the atmosphere is almost always humid and nearly saturated; there are no marked differences in degree of humidity such as affect profoundly the distribution of plants.

Soil reaction is probably the most potent factor, but there are certain phenomena, such as the mutual exclusiveness of *Nægleria* and *Hartmanella* (p. 443) which cannot yet be explained.

It is difficult to form an idea of what the soil population is like and how it lives; to construct the impression one would gain if one could shrink down to the size of a micro-organism and wander about in the soil. If the staining method could be developed to deal with all the organisms, it would prove very valuable. The statistical method (p. 416) gives the quantitative information, but, except for the protozoa, it fails to show the stage in the life-cycle in which any particular organism occurs. The bacteria are by far the most numerous, but they are the smallest; the amœbæ are fewer, but a single one may be a thousand times the size of a bacillus. The fungi and actinomycetes at present cannot be estimated so well as the others; their total weight may approach that of the bacteria: in acid conditions it may even be greater. A better picture of the soil population is obtained if, instead

of the numbers, the masses of the organisms are estimated. Making certain assumptions as to the volume of the organisms and taking Allison's [1] value (1·04 to 1·06; for algal cells, 1·1) for their density the figures in Table 81 are obtained:

TABLE 81.—NUMBERS AND ESTIMATE OF APPROXIMATE WEIGHTS OF PROTOZOA AND OF BACTERIA IN NEUTRAL ARABLE SOIL RECEIVING FARMYARD MANURE, ROTHAMSTED.

	Numbers per Gram of Soil.	Approximate Weight, lb. per Acre, Top 6 inches.	
		Live Weight.	Dry Matter.
Amœbæ	280,000	120	25
Flagellates . . .	770,000	*c.* 100	20
Ciliates	1,000	—	—
Bacteria	5,000,000,000	7500	1500
Algæ (excluding blue-green)	> 100,000	> 125	> 25

The fungi are not included, but their total numbers may be greater than those of the amœbæ, and their total mass may approach that of the bacteria.

they have no quantitative value whatsoever and serve only for illustration.

The total weight of organic matter in the top 6 inches is of the order of 40,000 to 50,000 lb. per acre so that the micro-organisms form only a small part—about 5 per cent.—of the whole. In arid soils, which are poorer in organic matter, the micro-organisms form a larger proportion, chiefly because of the marked development of Azotobacter under alkaline or saline conditions. Uspensky states that in the chestnut soils of South-East Russia, where up to 900 million Azotobacter per gram have been recorded, almost all the organic matter is in the form of micro-organisms.[2]

Our conception of the population would be improved if it were possible to take into account the rate of renewal of the organisms and their mobility and so allow for the speed with which they can get about in the soil to effect their various

[1] R. V. Allison, *Ann. Appl. Biol.*, 1924, **11**, 153.
[2] *Soil Microbiology in the U.S.S.R.*, 1933, p. 40.

changes. The Rossi-Cholodny method indicates the relative importance of the organisms as active agents in the soil, and the general order in which they attack freshly added material.

The Energy Supply.

The general requirements of the soil organisms are the same as those of plants ; *viz.* energy, nutrients, water, temperature, air, and absence of harmful conditions. The great difference is in the source of energy. Plants derive their energy from sunlight, fixing it by means of chlorophyll, while the soil population, apart from the autotrophic forms, derives it from preformed plant tissues brought into the soil by natural, or, on cultivated land, artificial agencies. It is this dependence on soil organic matter derived from plant residues that makes the common link between the members of the soil population. A few members, such as the algæ and green flagellates (Euglena, etc.) have a chlorophyll apparatus and can utilise the energy of sunlight, but they are not dependent on this method and retain always their habit of utilising the energy of soil organic matter. Others derive their energy from simple chemical oxidations (p. 353).

The organisms do not all derive their energy in the same way from the organic matter. There is a chain of decomposition processes ; some organisms beginning the decomposition and carrying it on to a stage where others can continue the action. As a general rule the number of organisms that can act increases as the degradation of the non-nitrogenous groups progresses from cellulose to sugars and fatty acids, and decreases as the nitrogen progresses from amides or amino-acid-through ammonia to nitrite and nitrate. With a few exceptions the reactions are not rigidly restricted to one group of organisms ; there is considerable interchangeability. But the chain of actions is governed by one inexorable law ; there is a certain amount of energy to be got by oxidation of a given weight of organic matter, and no more than this amount can

be extracted whatever the organisms, however they act, and whether there are one or many stages in the reaction. Further, no action is known that gives out more energy than the oxidation.

Moreover, the energy can be used only once. This constitutes a vital distinction between nutrients and energy. Nutrients can be used over and over again by an unending succession of micro-organisms; an atom of nitrogen never loses its value and might in the course of a single day form part of a fungus, a bacillus that decomposed it, an amœba that ate the bacillus, and a bacterium that decomposed the dead amœba; for all these organisms one and the same atom of nitrogen would be a perfectly good nutrient.

But energy cannot be used in this way. It is as indestructible as matter, but once transformed to heat, it cannot be used by micro-organisms or any other living things; whatever energy is dissipated by one organism becomes thereby for ever out of the reach of the others. It follows, therefore, that no factor, either internal or external, that affects the trophic life in the soil without adding to the stock of energy material or nutrients can permanently increase the numbers of all the groups; if one increases, others necessarily decrease.

So far as present knowledge goes, the soil organisms are living right up to their income in the matter of nutrients and energy supply. Any increase in available organic matter capable of supplying energy at once increases the numbers of micro-organisms; this is accompanied by an absorption of ammonia and nitrate from the soil to supply them with nitrogen. Of two plots, one supplied with farmyard manure and the other not, the unmanured plot always contains fewer organisms; fewer kinds and fewer of every kind yet enumerated. This is one of the few clear connections between numbers of organisms and external conditions.[1] Plots

[1] D. Fehér (*Arch. Mikrobiol.*, 1934, **5**, 421) shows that bacterial numbers found by plating methods are related to the output of CO_2 from forest soils, and also to the fluctuations in the percentage of CO_2 in the atmosphere.

receiving artificial fertilisers only and no organic matter carry a population of bacteria and protozoa similar in number and character to that of the unmanured land, though they may carry more fungi.

The supply of energy and nutrients thus becomes the chief factor determining the numbers of organisms in the soil. An exact measure of the amount of energy available to micro-organisms in a given weight of soil would be one of the most important quantities in soil microbiology. Unfortunately, no method is yet known for its determination. Combustion in a calorimeter gives the total quantity but does not show how much is available. An estimate of the amount of energy transformed in a given period can, however, be obtained by determining the total quantities at the beginning and at the end. Estimates obtained from analytical data for two of the Broadbalk plots are given for illustration only [1] in Table 82.

TABLE 82.—ANNUAL ENERGY CHANGES IN SOIL: BROADBALK. APPROXIMATE ESTIMATES ONLY.

Millions of Kilo-Calories per Acre per Annum.

	Farmyard Manure Added.	No Manure Added.
Added in manure . . .	14	Nil
,, in stubble . . .	2	0·3
Total added	16	0·3
Net loss from soil . . .	Nil	0·5-1
Stored in soil	0·5-1	Nil
Dissipated per annum . .	15	1
Per day: Calories . . .	41,000	2700
Equivalent to the requirements of	12 men	¾ man
The human food grown provides for	2 men	½ man

The increases in numbers resulting from addition of energy material is not uniform for all organisms but depends on the nature of the added substance and on the amount of nitrogen present. This is shown by the appearance of the plates; the

[1] See also F. H. H. van Suchtelen, *Zbl. Bakt.*, Abt. II, 1923, 58, 413.

new colonies arising from the increased numbers appear to belong to one or two kinds of organisms only. In the poor, unmanured soil of the Institut Pasteur at Brie-Comte-Robert, Winogradsky found only a few active organisms; three or four species of cocci, a few Azotobacter, a little mycelium of actinomycetes, and an occasional yeast, but no bacilli and no moulds. These were all the living things; he calls them the normal population for that particular soil.

Addition of an artificial preparation of humus gave an increase in numbers but no new forms; the flora still remained as restricted as before. Addition of carbohydrate or protein, however, led to a rapid change in the type of population; with peptone, after incubation at 30° C. for one night, the original population disappeared and was replaced by two kinds of bacilli in enormous numbers. The type of dominant organism could be varied by appropriate choice of carbohydrate; thus, addition of mannite led to a profuse growth of Azotobacter. Addition of starch was followed by a great increase in numbers, but two kinds of organisms predominated, a bacillus and a mass of actinomycetes.[1] After a short time, however, the population reverted to the normal type.

It is significant that humus alone gave the general uplift to all the normal inhabitants such as happens with increases in the organic matter content of normal soils.

The Process of Decomposition.

The effect of adding plant residues to the soil depends on the degree of ripening, *i.e.* of lignification, of the material. Additions of cellulose or straw cause a marked increase in the fungi, especially in slightly acid conditions.[2] On the other hand addition of succulent green material has little effect on fungi and actinomycetes but causes an enormous development of bacteria within and near the material and a rapid decom-

[1] S. Winogradsky, *Chimie et Industrie*, 1924, **11**.

[2] S. A. Waksman and R. L. Starkey, *Soil Sci.*, 1924, **17**, 373; H. L. Jensen, *J. Agric. Sci.*, 1931, **21**, 38.

position with evolution of CO_2 rising to a peak on the fourth day : afterwards a subsidence to the original level.[1]

The organic substances in the soil are decomposed in two different ways by the micro-organisms : they may be assimilated by the organisms and metabolised, simpler products being excreted ; or they may be decomposed with evolution of carbon dioxide, *i.e.* fermented. D. W. Cutler and L. M. Crump [2] find that the course of the decomposition turns on the age of the cultures and their position in regard to reproduction. Older cultures assimilate organic substances while reproduction is going on, but break them down to CO_2 while it is suspended : young cultures, on the other hand, carry out both processes simultaneously, liberating most CO_2 during their most active reproduction.

The organisms in the soil do not work independently of each other. They interact in two different ways. Competition is severe, a fact that sometimes makes plate cultures difficult, media having to be modified so as to restrict growth after it has proceeded sufficiently far. Some forms, especially among the fungi, seem particularly antagonistic to others, and hopes have been entertained that parasitic fungi might be kept in check by introducing saprophytic forms antagonistic to them but harmless to the plant. Protozoa are directly antagonistic to bacteria in that they feed on them.

On the other hand, symbiosis is common and joint action—perhaps one should more strictly say consecutive action—is the normal occurrence in the soil. The by-products or metabolic products of one organism, if they are anything more complex than CO_2 and water, are the starting-point for activity of other organisms ; and this activity is continued by one or other of the population so long as there is any potential energy of oxidation in the products, but no longer. There is no evidence whatsoever of the slowing down of micro-organic activity in normal soils by accumulation of oxidisable products

[1] N. R. Smith and H. Humfeld, *J. Agric. Res.*, 1930, **41**, 97.
[2] *Ann. Appl. Biol.*, 1929, **16**, 472.

corresponding to the slowing down in cultures ; no " bacterio-toxins " can be detected, and nothing to show that the " auto-intoxication " of pure cultures ever occurs in the soil.[1] The products that might have these effects are quickly attacked by other organisms ; the final products are CO_2 and nitrates, and both these are easily removed from soil.

Variations in Numbers and Activities of Organisms.

A remarkable property of the soil population, common to all groups, is that as the numbers of individuals increase so do the numbers of species. This is in marked contrast with the surface vegetation. On the Rothamsted grass plots the unmanured land carries the highest number of species of plants, but none of them grows vigorously ; doubtless the poor growth of all allows the chance of life to many not well suited to the conditions. Any scheme of manuring that increases plant growth acts differentially ; some species flourish more than others, and, in growing, crowd out their less vigorous neighbours ; the manured plots, while carrying more and larger individuals, have therefore fewer species.

One of the most striking properties of the soil population shown by all groups for which examination is possible is that the numbers do not remain constant, even under apparently constant conditions, but fluctuate continuously.

In some cases this may be the result of different modes of reproduction at different stages of the life cycle, *e.g. Bacillus radicicola* investigated by Thornton and Gangulee, which divides sometimes by binary and sometimes by multiple fission (p. 393). Taylor observed fluctuations in soil kept in an incubator at constant temperature and moisture content. Thornton and Gray, using the plating method, and Taylor, using both plate and microscope counts for sets of 2-hourly samplings, found no correlation between fluctuations in bacterial numbers in field soils and either temperature or

[1] H. B. Hutchinson and A. C. Thaysen, *J. Agric. Sci.*, 1918, **9**, 43.

moisture content. Apparently the bacterial numbers are not directly controlled by temperature and moisture; a sudden change in the soil conditions might, however, set up a series of fluctuations which continued after the change had ceased. The fluctuations may represent an inherent instability in the micro-population; indeed Cutler and Crump consider that for most organisms it seems necessary to assume an innate capacity of protoplasm to behave rhythmically.[1]

Whatever the cause, if one group of organisms begins to fluctuate in number, it almost necessarily involves others. Fluctuation of protozoan numbers is associated with an inverse fluctuation of bacterial numbers (p. 446).

If we assume that the soil organisms are living right up to the energy and nutrient supplies, it follows that any increase in one group, not accompanied by an increase in energy material, must depress the numbers of near competitors, but this again may allow a third group to multiply.

Superimposed upon the daily fluctuations are the great seasonal changes; for all groups so far studied there is a tendency to greater numbers and higher activity in spring and autumn, and lower numbers and lower activity in winter and summer. Thus T. M. Zacharova, working with a podzol, found peaks in the numbers of *B. Stutzeri* at the end of May and again in August,[2] and N. G. Potapof obtained similar fluctuations on a chernozem soil.[3] J. K. Wilson obtained peaks in October and again in June for two species of legume nodule bacteria.[4]

Presumably, activity of the micro-organisms fluctuates along with their numbers, but this is not easy to determine. Fluctuations of *p*H values are recorded. A seasonal rise in acidity was observed by Smith and Robertson on uncropped land during the summer months, but not on land on which potatoes were growing. They associated the rise with

[1] D. W. Cutler and L. M. Crump, *Problems in Soil Microbiology*.
[2] *Trans. Inst. Fertilizers*, Moscow, 1929, No. 60.
[3] *Ibid.*, No. 76, 92.
[4] *Soil Sci.*, 1930, **30**, 289.

changes in the quantities of electrolytes present in the soil; these could accumulate on the uncropped, but not on the cropped land.[1] Variations in the arid forest soils of Central Europe are recorded by D. Fehér and attributed by him to the fluctuating activities of the soil micro-organisms.[2] Drought, the summer season, and rainfall are all recorded as having lowered the *p*H,[3] but Salminen[4] found in Finland that, coming immediately after a drought, rain first raised the *p*H and then after long continuance lowered it. These changes are presumably due to changes in the quantities of electrolytes in the soil. The citric-soluble phosphate of forest soils also fluctuates: it is lowest in summer and highest in autumn and winter.[5]

The only factor known to raise the numbers of all alike is energy supply, and the phenomena seem to be precisely as if additional energy supplies were brought into the soil during spring and autumn and not during summer and winter. But the cause may be much more deep-seated; plankton in sea,[6] algæ in lakes and rivers fluctuate in much the same way, being most numerous in spring and autumn, and the phenomena may be related.[7] Atkins and Harris[8] show that in ponds the *p*H of the water also varies with the season, being high (*i.e.* alkaline) in spring and autumn and lower in winter and summer. Similar changes have been observed in the soil by K. Boresch and R. Kreyzi[9] whose curves for fluctuations in *p*H value closely resemble those of Russell and Appleyard (1917) for CO_2 evolution.[10]

[1] A. M. Smith and I. M. Robertson, *J. Agric. Sci.*, 1931, **21**, 822.

[2] D. Fehér, *Arch. Mikrobiol.*, 1934, **5**, 402; *Bot. Arch.*, 1933, **36**, 53.

[3] L. D. Baver, *Soil Sci.*, 1927, **23**, 399; A. Løddesøl, *Jordundersøkelsens Småskryfl*, Oslo, 1932, No. 21; A. P. Kelley, *Soil Sci.*, 1923, **16**, 41; J. R. Swanback and M. F. Morgan, *Conn. Agric. Expt. Sta. Bull.* 264, 1930.

[4] A. Salminen, *J. Sci. Agric. Soc.*, Finland, 1933, **5**, 1.

[5] D. Fehér, *Phosphorsäure*, 1934, **4**, 508.

[6] W. A. Herdman, *J. Linn. Soc. Bot.*, 1922, **46**, 141.

[7] W. West and G. S. West, *ibid.*, 1912, **40**, 395.

[8] *Notes from Botanical School of Trin. Coll. Dublin*, 1922, **3**, 281.

[9] *Fortschr. Landw.*, 1928, **3**, 963.

[10] *J. Agric. Sci.*, 1917, **8**, 385. For a fuller discussion see Cutler and Crump, *Problems in Soil Microbiology*, 1936, p. 85.

Although variations in water supply and in temperature do not alter the numbers of soil micro-organisms in any predictable way, the total activity of the population so far as it can be estimated by the rates of oxygen absorption, of CO_2 evolution, or nitrate production, is increased by increases in water supply or temperature up to the optimum range as would *a priori* be expected.[1] Thus, for a chalky loam, the following relative results were obtained :—[2]

Moisture present . . .	Air dry (7·4 per cent.)	20 per cent. added	25 per cent. added
Oxygen absorbed in 23 days .	6·5	21·67	27·7

The effect on nitrate production is shown in Table 83 and Fig. 51.

TABLE 83.—EFFECT OF TEMPERATURE OF STORAGE ON BACTERIAL NUMBERS AND NITRATE PRODUCTION. RUSSELL AND HUTCHINSON (1913).

Temperature of Storage.	Bacteria, Millions per Grm. of Dry Soil.			Nitrate and Ammonia, Parts per Million of Dry Soil.		
	At Start.	After 10 Days.	After 50 Days.	At Start.	After 10 Days.	After 50 Days.
7°-12°	16	16	16	17	18	22
20°		12	21		16	30
30°		15	14		24	36
40°		9	14		55	76

The efficiency of the individual members of the population of soil micro-organisms falls off as the numbers rise. Table 84 shows results obtained at Rothamsted : the quantity of CO_2 evolved from soil per million organisms falls as the population rises, no matter what the previous history of the soil has been. A mixed population of bacteria and amœbæ may be more

[1] E. M. Delf, *New Phytol.*, 1915, **14**, 63 (Hampstead ponds) ; W. and G. S. West, *J. Linn. Soc. Bot.*, 1912, **40**, 395 (English lakes) ; C. A. Kofoid, *Bull. Ill. State Lab. Nat. Hist.*, 1903 and 1908 (Illinois River) ; W. R. G. Atkins and G. T. Harris, *Proc. Roy. Soc. Dublin*, 1924, **18**, 1-21.

[2] E. J. Russell, *J. Agric. Sci.*, 1906, **1**, 266.

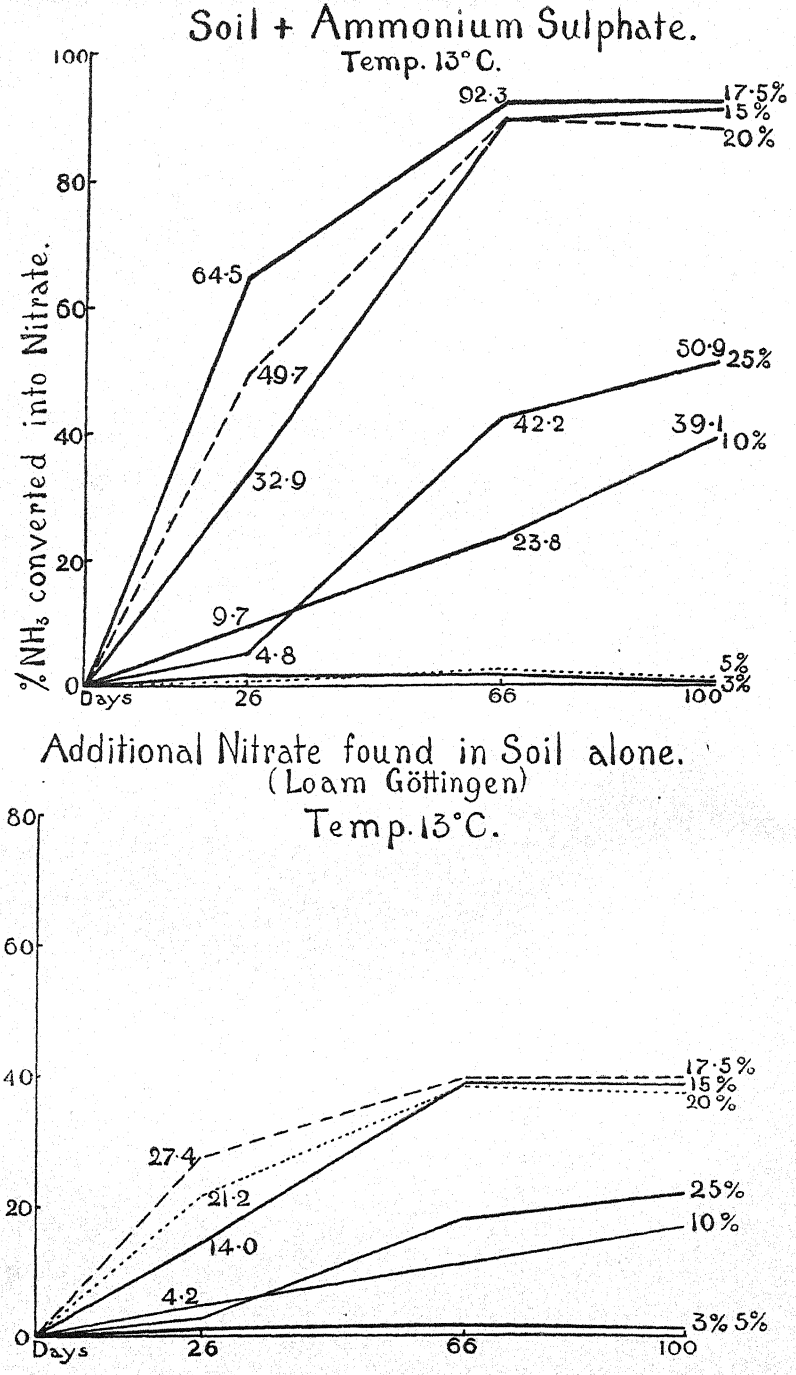


FIG. 51.—Effect of moisture on the nitrification process in soil. A. E. Traaen, *Zbl. Bakt.*, Abt. II, 1916, **45**, 119.

efficient for producing CO_2 than a population of bacteria alone,[1] presumably because the presence of amœbæ keeps the culture young by lowering the duration of life of the bacteria.[2]

TABLE 84.—MILLIGRAMS OF CARBON DIOXIDE GIVEN OFF FROM THE SOIL AT DIFFERENT DENSITIES OF BACTERIAL POPULATION. THE RESULTS ARE CALCULATED PER 1000 MILLION BACTERIA IN EACH CASE.

Manuring.	Numbers of Bacteria in Millions per Grm.				
	0–200.	200–400.	400–600.	600–800.	Over 800.
Farmyard manure	0·245 (2)	0·140 (2)	0·126 (7)	0·098 (3)	0·039 (33)
No manure . .	0·149 (12)	0·053 (9)	0·055 (1)	0·049 (2)	0·049 (2)
Complete artificial manure, including nitrate of soda . .	0·365 (24)	0·058 (10)	0·062 (5)	0·029 (1)	—
Complete artificial manure, including sulphate of ammonia .	0·190 (16)	0·091 (7)	—	—	0·041 (1)

The figures in brackets refer to the number of cases from which the average amount is derived.

EFFECT OF CONDITIONS: SOIL REACTION.

The effect of the soil reaction on the soil population differs with the different members. Certain bacteria and some of the larger animals, especially earthworms and snails, are most influenced by soil acidity; fungi and protozoa apparently less so. Within each group the members are differently affected.

Variations in acidity therefore cause variations in flora: usual limits of tolerance of acidity for some of the common bacteria are shown in Table 85.

The activity of the soil population is greatest at about a neutral reaction (*p*H 7), but some of the actions are further

[1] L. de Telegdy-Kováts, *Ann. Appl. Biol.*, 1932, **19**, 65.

[2] For efficiency and ammonia production in bacteria, see Jane Meiklejohn, *Ann. Appl. Biol.*, 1930, **17**, 614; 1932, **19**, 584. For the general question of population and reproduction, see W. C. Allee, *Animal Aggregations* (Univ. Chicago Press, 1931), and Raymond Pearl, *The Biology of Population Growth*, Williams & Norgate, 1926.

TABLE 85.—TOLERANCE OF ACIDITY BY VARIOUS SOIL ORGANISMS.

Organism.	Minimum *p*H Tolerated.	Author.	Reference.
Nitrosomonas .	3·9	T. Gaarder and O. Hagem	*Bergens Museums Aarbog*, 1922-1923, No. 1.
Nitrobacter .	3·9	C. S. Meek and C. B. Lipman	*J. Gen. Physiol.*, 1922. **5**, 195-204.
Azotobacter .	5·6	U. Yamagata and A. Itano	*J. Bact.*, 1923, **8**, 521-531.
Bact. radicicola.	3·1-5·0	E. B. Fred and A. Davenport	*J. Agric. Res.*, 1918, **14**, 317-334.
B. subtilis .	4·2	A. Itano	*Mass. Agric. Expt. Sta. Bull.* 167, 1916.
Thiobacillus thio-oxidans .	< 1·0	S. A. Waksman and R. L. Starkey	*Proc. Soc. Expt. Biol. Med.*, 1922, **20**, 9-14. *J. Gen. Physiol.*, 1923, **5**, 285-310.
Cellulose-decomposing vibrios	6·4	H. L. Jensen	*J. Agric. Sci.*, 1931, **21**, 81-100.

increased by adding more calcium carbonate. Nitrification in particular is increased, but not, apparently, ammonification. The numbers of organisms are also greatest about *p*H 7. In consequence, addition of lime to an acid soil does not necessarily increase the amount of nitrate; both in Stephenson's [1] and Hall's [2] experiments the limed soil usually contained less than the unlimed, presumably because of the reduced ammonification and increased assimilation of nitrate by the additional organisms. Hesselman [3] found that ammonification was most active in Swedish forest soils between *p*H 4·5 and 5, while nitrification was at a maximum at *p*H 6 or more. Comparing soils of various calcium contents he found a maximum nitrification when 2·0 to 2·5 per cent. of CaO was present.

[1] R. E. Stephenson (Kentucky), *Soil Sci.*, 1921, **12**, 133-144.

[2] T. D. Hall (Potchefstroom), *ibid.*, 301-363. For difference in action between calcium oxide and carbonate see H. B. Hutchinson and K. MacLennan, *J. Agric. Sci.*, 1914, **6**, 302.

[3] *Medd. Skogsförsöksanst.*, 1926, **22**, 169 (long German summary).

Soluble Salts.

The effects of soluble salts and of soil alkali on the micro-organisms of the soil have been much studied in the Western United States, especially by C. B. Lipman in California (1912), J. E. Greaves and his co-workers in Utah (1916, 1922), and W. G. Sackett and Collins in Colorado. Beyond a certain concentration soluble salts are harmful; indeed, it is possible by measuring the reduction in activity of the micro-organisms (using CO_2 production, ammonification, etc., as the measure) to form an estimate of the wheat-yielding power of an alkali soil.[1] But lower concentrations decidedly stimulate the action of all the micro-organisms yet studied. The extent of stimulation and the critical concentration beyond which further increases produce injury vary with different organisms. Azotobacter is most tolerant; the various ammonia-producing organisms come next, and the nitrifying organisms are least tolerant; wheat seedlings are intermediate in tolerance between ammonia producers and nitrifiers. The different salts vary in their effects; in general chlorides are the most toxic, while nitrates, sulphates, and carbonates are successively less toxic to the ammonifying organisms: the order is almost reversed, however, for the nitrifiers, being: CO_3 (most toxic) $> NO_3 > SO_4 > Cl$.[2] Usually the more toxic the salt, the greater its power of stimulation at low concentrations. Table 86 shows typical results obtained by J. E. Greaves and his colleagues; the effects, however, are not constant, but vary with the soil and other conditions.

Movement of Organisms in the Soil.

Thornton and Gangulee[3] have successfully adapted Winogradsky's method to study the rate of movement of

[1] J. H. Barnes and Barkat Ali, *Agric. J. India*, 1917, **12**, 368; see also S. M. Nasir, *Pusa Bull.* 145, 1923.

[2] For discussion of relation to osmotic pressure see J. E. Greaves, *Bot. Gaz.*, 1922, **73**, 161.

[3] See Chap. V, pp. 393-395.

micro-organisms in the soil. *Bacillus radicicola*, with which alone they experimented, moved in favourable conditions at the rate of 1 inch in twenty-four hours, a value which lends support to the older estimates of 1 inch in forty-eight hours in natural soils.

Using similar methods with mixtures of bacteria and protozoa, L. Losina-Losinsky and P. F. Martinov [1] showed

TABLE 86.—PERCENTAGES OF VARIOUS SALTS IN LOAM SOIL, WHICH ARE NECESSARY TO REDUCE AMMONIFICATION, GERMINATION, AND DRY MATTER PRODUCED IN WHEAT TO ABOUT HALF NORMAL.[2]

	Wheat Seedling to Half Normal.	Ammonification to Half Normal.	Nitrification to Half Normal.
Sodium chloride .	0·20	0·117	0·234
Calcium ,, .	·30	·222	—
Potassium ,, .	·25	·298	·298
Magnesium ,, .	·40	·381	·006
Potassium nitrate .	·40	·607	·101
Sodium ,, .	·30	·850	·170
,, sulphate .	·55	·852	·568
Magnesium ,, .	·70	·963	·361
Sodium carbonate .	·30	1·166	·212
Magnesium nitrate .	·45	1·187	·074
Potassium sulphate .	·60	1·394	·349
,, carbonate .	·70	1·520	·138

that *Amœba Vahlkampfia* moved somewhat more slowly than the bacteria, and ciliates more slowly still, in normal moisture conditions—15 to 20 per cent. of moisture, corresponding to 25 to 40 per cent. of the water-holding capacity. At higher moisture contents all the protozoa, including ciliates, became actively motile.

Reference has already been made (p. 443) to the fact that soil absorbs protozoa from a suspension: 1 grm. of Rothamsted soil will hold tenaciously 1½ to 2 million protozoa. Beyond a certain point, however, there is no further absorption: the phenomena are as sharp as those of titration and quite different

[1] *Soil Sci.*, 1930, **29**, 349.

[2] J. E. Greaves, E. G. Carter, and H. C. Goldthorpe, *J. Agric. Res.*, 1919, **16**, 107; see also J. E. Greaves, *Soil Sci.*, 1918, **6**, 163; 1922, **13**, 481.

from those of ordinary absorption where there is no definite end-point. At saturation the protozoa still appear to have plenty of room. The surface of a gram of Rothamsted soil cannot be closely estimated, but it probably exceeds 2000 sq. cm. But the amœbæ and flagellates retained by it would occupy little more than 4 sq. cm. if set down regularly on a flat surface in close formation. Why they cannot pack closer in the soil is difficult to understand.

Bacteria are similarly absorbed, but it is not known whether "saturation points" exist for them and for other organisms, the experimental difficulties not having been overcome.

Relationship of the Soil Population to Plant Growth.

The fundamental relationship between the soil population and plant growth is that the soil population decomposes the plant residues in the soil thereby obtaining nutrients and energy, and the process taken as a whole is advantageous to the plant.

The plant benefits in several ways :—

Nutritive Effects.—(*a*) *Decomposition Products.*—Some of these, nitrates and the ash constituents, are direct plant nutrients ; others may have a stimulating or other action on plant growth, though this is not certain.

Other products, including the colloidal complex humus, improve the physical conditions of the soil for the plant, while the unaltered plant material may injure the physical conditions.

(*b*) *Products of Synthesis.*—Some of the algæ may increase the supply of organic matter, and some of the bacteria fix gaseous nitrogen, thus increasing the stores of plant food material in the soil.

(*c*) *Scavenging Effects.*—Some of the intermediate products of decomposition would be harmful if they accumulated, *e.g.* certain phenolic substances, but they are speedily oxidised and rendered innocuous by micro-organisms.

In addition to these effects there is also the possibility that some of the saprophytic organisms may be detrimental to the activities of the parasitic organisms, and so help to keep them in check.

The plant, however, may suffer in two ways :—

(1) The soil organisms take up nitrates, phosphates, and other mineral nutrients from the soil, and appear to be able to get them more readily than the plant. Thus, addition of organic matter containing 4 or 5 per cent. of nitrogen is commonly followed by an increased production of nitrate and enhanced fertility. But should the organic matter contain only 1 or 2 per cent., there may be an absorption of existing nitrate and a temporary decrease in fertility (p. 349) though the microbic population increases.

(2) Certain of the soil organisms, *e.g.* the parasitic forms, may directly injure the plant.

The micro-organisms benefit by the growth of plants because the greater the growth the more energy material will be brought into the soil.

But the benefit is not immediate ; the growing plant may, indeed, depress the growth of micro-organisms.

These various actions are all concurrent ; their resultant represents the effect of the soil population on fertility.

Increases in nutrient supplies lead to increased activity of the micro-organisms. Hendrick,[1] in lysimeter experiments, finds that the amount of nitrate derived from the soil (which measures the amount of ammonia produced) is greater on soils receiving large quantities of artificial fertilisers than in unmanured soils. The quantities in lb. per acre over a period of fifteen months are (see table on p. 473).

The seasonal fluctuations which are a marked feature of the numbers of organisms show up equally clearly for the products of their activity. The production of CO_2 and of nitrate is more rapid in spring and autumn, less rapid in winter

[1] *Scot. J. Agric.*, 1924, **7**, 8. The differences are usually less than these.

	No Manure Added.	Sulphate of Ammonia Added.	Sulphate of Ammonia and Superphosphate.	Sulphate of Ammonia, Superphosphate and Muriate of Potash.
Total nitrate in crop and drainage water .	193	774	792	776
Nitrate supplied by manure .	—	475	475	475
Nitrate from soil	193	299	317	301

and sometimes in summer.[1] The rate of decomposition of organic matter in soils varies in the same way.[2] There are consequential changes in the bases which, however, have not been fully worked out. The spring activity is specially well marked ; it has been a tradition among gardeners and farmers from time immemorial.[3] It was studied by Löhnis and Sabaschnikoff at Leipzig [4] and under the picturesque title of *Le Réveil de la terre*, by Müntz and Gaudechon.[5] Fig. 29 (p. 239) shows the Rothamsted results. Leather in India [6] and Jensen [7] in South Dakota obtained similar results. The evidence in regard to decreased activity in summer is not as strong as that of rapid activity in spring. The number of experimental points is usually only small.

[1] Russell and Appleyard (1917) ; H. Reinau, *Zeit. Ver. Deut. Ingenieure*, 1925, **69**, 720 ; see also Boresch and Kreyzi, *Fortschr. Landw.*, 1928, **3**, 963.

[2] W. E. Isaac, *J. Ecology*, 1934, **22**, 289.

[3] *Cf.* Virgil, *Georgics*, Bk. II, 324-327 :—

> vere tument terrae et genitalia semina poscunt.
> tum pater omnipotens fecundis imbribus aether
> coniugis in gremium laetae descendit et omnis
> magnus alit magno commixtus corpore fetus.

[4] *Zbl. Bakt.*, Abt. II, 1908, **20**, 322 ; also Löhnis, *Handbuch der landwirtschaftliche Bakteriologie*, 1910, Berlin.

[5] A. Müntz and H. Gaudechon, *C.R.*, 1912, **154**, 163.

[6] J. W. Leather, *India Mem. Dept. Agric.*, Chem. Ser., 1912, **2**, 63.

[7] C. A. Jensen, *U.S.D.A. Bur. Plant Indust. Bull.* 173, 1910.

The change in nitrate content of the soil is important in view of the fact (pp. 39, 240) that plants assimilate most of their nitrogen in the early days of their growth.

But when one gets away from the great simple outlines, the details of the relationships are very complex. Among the most interesting results are the curious reversals of activity sometimes observed, which make the path of the dogmatist in soil microbiology peculiarly treacherous.

Addition of nitrogenous matter may increase or decrease the amount of the soil nitrogen according to the conditions. In neutral soils of cool climates, *Bacillus radicicola* is the most active fixer of nitrogen and Azotobacter is relatively inactive; lucerne, therefore, enriches the soil in nitrogen while wheat stubble does not. In alkaline soils of warm climates, on the other hand, Azotobacter is greatly stimulated; *Bacillus radicicola* is not; wheat stubble, therefore, tends to enrich the soil in nitrogen while lucerne has hardly any effect (p. 404).

Still more remarkable are the strikingly unexpected results of treating the soil in ways calculated to injure the trophic life; drying, treating with poisons, heating, etc. Instead of decreasing the activity of micro-organisms these treatments tend to increase it, at any rate for certain groups (p. 477).

The relative simplicity of the effects of moisture and temperature on the amount of decomposition when studied only in broad outlines, and the difficulties encountered when one comes down to details, account for the limited success attained in the attempts to trace simple relationships between specific activities of the micro-organisms and soil fertility. Soils differing only in their content of organic matter present the simplest case; if they are otherwise comparable the differences in numbers of micro-organisms or in the amounts of their products run fairly closely with differences in fertility. Soils differing in reaction also show relationships between activity of micro-organisms and fertility, as also, though in a more restricted way, do soils differing in phosphate content.

Microbiological Analysis of Soil.

The relationship between soil micro-organisms and soil fertility has led to the development of microbiological methods for the examination of soil.

Two types of method have been used :—

(1) Methods assuming a causal relationship between soil fertility and activity of micro-organisms: these include estimations of the power of the soil population to perform essential processes such as the production of ammonia or of nitrates.

(2) Methods assuming no causal relationship but based on the recognition that soil micro-organisms have the same general requirements as plants. Soil in which plants grow well are also soils of high micro-organic activity as shown by the rate at which they absorb oxygen.[1] Instead therefore of making pot cultures with plants to ascertain soil deficiencies it should suffice to make culture experiments with bacteria, which can be done much more rapidly and requires much less space.

The first group of methods is the older and as already stated (p. 414) it did not give particularly useful results so that it has been generally abandoned. The second group, however, has proved of value and still survives for testing purposes.

Of the various soil bacteria used for cultures Azotobacter and the nitrifying organisms yield the most useful results. Three different practices are at present adopted :—

(1) *Diagnosis of Lime Deficiency.*—This is based on the sensitiveness of Azotobacter to acidity (p. 385); it was introduced by Christensen in 1911[2] and was much used in Denmark till the more convenient physico-chemical methods were developed.

[1] E. J. Russell, *J. Agric. Sci.*, 1905, **1**, 261; 1907, **2**, 305 (with F. V. Darbishire).

[2] H. R. Christensen and O. H. Larsen, *Zbl. Bakt.*, Abt. II, 1911, **29**, 347.

(2) *Phosphoric Acid Requirement.*—Azotobacter is equally sensitive to supplies of phosphate in the soil and was used by Christensen [1] for grading soils into those that needed further additions and those that did not. The method has been developed by Niklas.[2] Aspergillus [3] and *Cunninghamella* [4] have been used for the same purpose.

(3) *General Fertility Conditions.*—Winogradsky and J. Ziemięcka [5] have shown that Azotobacter can be used for indicating general fertility conditions.

Ziemięcka has shown that the nitrifying organisms serve the same purpose.[6] Rapid nitrification occurs in soils rich in neutral organic matter, *e.g.* garden soils; the process is slower in fields with *p*H values above 6·3 and slowest in acid soils. The method affords no test of the phosphate supplies of soil, since nitrifying organisms require but little for their development. Methods based on the use of Azotobacter are much in favour in Russia.[7]

The Effect of Simplifying the Soil Population: Partial Sterilisation.

In the preceding pages several instances have been given of treatments detrimental to trophic life increasing the activity of the surviving members of the soil population and particularly of the bacteria.

Relatively mild treatments, such as drying the soil, heating

[1] H. R. Christensen, *Soil Sci.*, 1923, **15**, 329; E. J. Petersen, *Tidskr. Planteavl*, 1926, **32**, 625; S. A. Waksman and P. D. Karunakar, *Soil Sci.*, 1924, **17**, 379.

[2] H. Niklas, H. Poschenrieder, and A. Hock, *Zbl. Bakt.*, Abt. II, 1926, **66**, 16.

[3] A. M. Smith, *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 171. *J. Soc. Chem. Ind.*, 1936, **55**, 217T.

[4] A. Mehlich, E. B. Fred and E. Truog, *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 168.

[5] *Ann. Inst. Pasteur*, 1928, **42**, 36.

[6] J. Ziemięcka, *Akad. Nauk Tech.*, Warsaw, 1930, Part 4.

[7] E. E. Uspensky and A. P. Kriutchkova in *Soil Microbiology in the U.S.S.R.*, Moscow, 1933.

to 45° C., treatment with poisons which are not too strong,[1] cause a fall in numbers of bacteria, but when the conditions are again made suitable, the numbers rise considerably. They do not remain high, but sooner or later fall to the normal range of values.

More drastic treatment, such as heating the soil to 50° C. (at which temperature most of the trophic forms are killed), or treatment with certain stronger poisons, also causes a fall and subsequent rise in bacterial numbers when favourable conditions are restored, but the high numbers are maintained much longer. The phenomena are not confined to soil but are shown also by other complex microbial associations, such as sewage beds.[2] According to Waksman and Starkey [3] the fungi in soil are first much depressed, but increase greatly in numbers soon after the conditions again become favourable. The actinomycetes are also at first depressed, though nothing like as much as the fungi: they do not recover as quickly as the bacteria though they multiply rapidly if cellulose or other energy material be added. Russell and Hutchinson showed that the numbers of bacteria in partially sterilised soils, unlike those in normal soils, reacted in accordance with expectation towards changes in temperature and water content.

As a general explanation the writer suggested that the treatment, by curtailing or eliminating (according to its severity) one or more of the groups of the soil population,

[1] The effect of poisons was first observed by Oberlin in Alsace (*Bodenmüdigkeit und Schwefelkolhlenstoff*, Mainz, 1894) and has been much studied in France by G. Truffaut; Rivière and Pichard (*Ann. Sci. Agron.*, 1922, **39**, 366); Miège; and others. Iyer, Rajazpolan and V. Subrahmanyan (*Proc. Indian Acad. Sci.*, 1935, **2**, 108) used potassium permanganate.

[2] The disinfection of sand filters leads to increases in the numbers of bacteria. This was observed in the typhoid epidemic at Lincoln in 1904, and also in the experimental sewage filter at Guildford in 1907 (Houston and McGowan, *5th Rept., Sewage Commission*, Appendix IV, Cd. 4282, 1910, p. 111).

[3] S. A. Waksman and R. L. Starkey, *Soil Sci.*, 1923, **16**, 137, 246, and 343.

leaves the others more free from competition, and, therefore, able to increase to higher numbers than before and also to react normally to changes in external conditions. This view was put in more concrete form in conjunction with H. B. Hutchinson,[1] and evidence was adduced that bacteria, at that time regarded as the only living organisms in the soil, were not so in fact, but that other organisms were normally present keeping down their numbers. It was shown that these organisms were probably protozoa, a view that Cutler has since substantiated (p. 442).[2]

The organisms surviving partial sterilisation produce more ammonia and nitrate than did the original population, so that soils treated by methods calculated to injure trophic life gain in fertility, an apparently paradoxical result in view of the importance of trophic life to soil fertility (Table 87).

The fact has long been known to cultivators of the soil. Heating the soil has been practised from time immemorial in India; the process is called "rab," and is mentioned in the Vedas;[3] the burning of stubble was known by the Romans to increase the fertility of the soil, and various possible explanations were shrewdly put forward by Virgil.[4] Exposure of the soil to the baking heat of the sun is an ancient practice still common in India[5] and in Egypt, where it is known as *sheraqi*, and has been studied by J. A. Prescott[6] and shown to be due partly to micro-biological, and partly to physical, causes. Lebediantzev[7] considers that this repeated drying

[1] E. J. Russell and H. B. Hutchinson, *J. Agric. Sci.*, 1909, **3**, 111; 1913, **5**, 152.

[2] For a study of the effect of naphthalene on the bacterial and protozoan populations of greenhouse soils, see S. E. Jacobs, *Ann. Appl. Biol.*, 1931, **18**, 98.

[3] Like to a tender plant whose roots are fed,
On soil o'er which devouring flames have spread.
Stories of the Buddha's Former Births. Trans. H. L. Francis.

[4] *Georgics*, Bk. I, 84-93.

[5] A. and G. L. C. Howard, *Nature*, 1910, **82**, 456.

[6] *J. Agric. Sci.*, 1919, **9**, 216; 1920, **10**, 177.

[7] *Soil Sci.*, 1924, **18**, 419.

TABLE 87.—CHANGES PRODUCED IN SOIL BY PARTIAL STERILISATION. WEIGHT AND COMPOSITION OF CROPS GROWN ON PARTIALLY STERILISED SOILS. DARBISHIRE AND RUSSELL (1907).

	Dry Weight of Crop.	Percentage Composition of Dry Matter.			Weight of Nutrients Taken by the Plant from Soil, grms.		
	Grms.	N.	P_2O_5.	K_2O.	N.	P_2O_5.	K_2O.
Buckwheat:							
Untreated soil .	18·14	2·75	1·87	5·62	·499	·339	1·019
Soil treated with carbon disulphide .	23·27	3·15	2·34	5·97	·733	·544	1·389
Mustard:							
Untreated soil .	15·88	2·30	1·00	4·20	·367	·159	·668
Heated soil	24·33	4·43	2·08	5·02	1·077	·506	1·221

AMMONIA AND NITRATE ACCUMULATING IN A SOIL KEPT TWENTY-THREE DAYS AT ABOUT 15° C. IN A MOIST CONDITION, PARTS PER MILLION OF DRY SOIL. RUSSELL AND HUTCHINSON (1909).

	Nitrogen Present as Ammonia.		Nitrogen Present as Nitrates.		Total Nitrogen Present as Ammonia and Nitrate.		
	At Beginning.	After 23 Days.	At Beginning.	After 23 Days.	At Beginning.	After 23 Days.	Gain in 23 Days.
Untreated soil .	1·8	1·7	12	16	13·8	17·7	3·9
Soil heated 2 hours to 98° C. . .	6·5	43·8	13	12	19·5	55·8	36·3
Soil treated with toluene, which was then evaporated .	5·0	27·8	12	12	17·0	39·8	22·8
Soil treated with toluene, which was not removed .	7·2	14·5	11	10	18·2	24·5	6·3

and heating of the soil plays no small part in maintaining its fertility in hot countries. The effects on the plant are in all cases described as resembling those of nitrogenous manure.

This increased production of ammonia and nitrate is not a necessary consequence of the higher numbers of organisms ;

on the contrary higher numbers, *e.g.* those induced by adding non-nitrogenous organic matter to the soil, might depress the ammonia and nitrate content (p. 350) by taking up these substances for their own nutrition. The increased production of ammonia and nitrate is a distinct phenomenon, and several explanations have been put forward to account for it.

Hiltner and Störmer (1903), who were the first to associate the beneficial effects of partial sterilisation with bacteria,[1] considered that the new bacterial flora set up after the treatment was more potent in decomposing protein than the old one. This view was shown to be inaccurate by Russell and Hutchinson, who replaced the old flora by inoculating untreated soil into partially sterilised soil, and showed that the bacterial numbers rose even higher, and produced even more ammonia and nitrate, than did the new flora by itself.

The idea was modified by S. A. Waksman and R. L. Starkey (1923), who suggested that in normal soil much of the decomposition of the protein is effected by fungi, which assimilate a good deal of the carbon and a corresponding amount of nitrogen; after partial sterilisation, however, the fungi are for a time suppressed and the decomposition passes to the bacteria which assimilate much less of the carbon and nitrogen and, therefore, produce a larger amount of ammonia.

Russell and Hutchinson connected the increased ammonia production with the increased numbers of bacteria, supposing that the new bacterial flora was not widely different from the old, and might therefore be expected to behave like the old, except that, being more numerous, it would accomplish more decomposition. The close relationship between bacterial numbers and ammonia (or nitrate) production in their experiments supported this view. Störmer suggested that the additional ammonia and nitrate came from the decomposition by bacteria of the organisms killed by the partial sterilisation process. The amounts formed, however, are much larger

[1] The earlier investigator, A. Koch, had attributed the increased productiveness to a direct stimulation of the plant.

than correspond with our present estimates of the soil population; in the Rothamsted soil they are of the order of 20 to 50 parts of nitrogen per million of soil, while the whole protozoan and bacterial population represents only 4 parts: estimates of the nitrogen in soil fungi are, however, only rough.

The phenomena are complicated by the circumstance that partial sterilisation, however it is done, affects the colloids and the organic matter of the soil. The effect of heat has been much studied; [1] it is shown to bring about considerable decomposition of the organic matter, and thus to go some way towards the production of ammonia and nitrate. S. U. Pickering [2] showed that antiseptics had the same kind of effects but to a less degree. All these factors affect the relations between the increased numbers of bacteria and the increased production of ammonia and nitrate in partially sterilised soils.

[1] S. U. Pickering, *J. Agric. Sci.*, **3**, 171; F. J. Seaver and E. D. Clark, *Biochem. Bull.*, **1**, 413; O. Schreiner and E. C. Lathrop, *U.S.D.A. Bur. Soils*, Bull. No. 89, 1912.

[2] *J. Agric. Sci.*, 1908, **3**, 32.

CHAPTER VII.

THE BIOTIC CONDITIONS IN THE SOIL.

In the preceding chapters we have dealt separately with the plant and the soil; we shall now deal with them jointly and discuss the relationships between the soil properties and the growth of the plant. The conditions directly and markedly influencing the life of the plant, which may be called the chief biotic conditions in the soil, are air supply, water supply, temperature, supplies of nutrients, tilth, reaction, and possible toxins.

Air Supply: the Gas Phase of the Soil.

The soil being a porous mass, air can enter and pass out both by direct streaming and by diffusion. The amount that enters, and the rate of entry, depend on the pore spaces which in turn are determined by the sizes, shapes, and modes of arrangement of the soil particles. But the pore space has also to hold the soil water, so that a knowledge of its amount gives only the maximum space available for air. The space actually occupied by air at any time is approximately this maximum, less the space occupied by the water present.

If the soil particles were all spherical, the pore space could be studied mathematically. C. S. Schlichter [1] has shown that it would constitute 47 per cent. of the total volume if the particles were arranged in the most open fashion, and 26 per cent. if they were packed as closely as possible.

[1] *U.S. Geol. Survey*, 19th Ann. Rept., 1899. For further developments see W. B. Haines, *J. Agric. Sci.*, 1925, **15**, 529. C. E. Marshall points out that this is not the most open packing and that even larger pore spaces are theoretically possible.

For natural soils, however, no suitable mathematical treatment has been devised, and an experimental estimate is therefore made. At Rothamsted a known volume of the soil is taken *in situ* with a special sampling tool, a 9-inch cubical frame of steel, with a cutting edge at the bottom and a wide enough rim at the top to permit of the use of a mallet to drive it in. This sample is sufficiently large not to disturb the structure. The sample is dried and weighed, the true specific gravity of the particles is determined, and the volume of the solid matter is calculated. The pore space is the difference between this volume and that of the whole soil.

Table 88 shows the pore spaces for certain Rothamsted

TABLE 88.—PORE SPACE, WATER CONTENT, AND AIR CONTENT OF CERTAIN SOILS. RUSSELL.

	Specific Gravity of Dry Soil.		Volume Occupied in Natural State by		Volume of Water.		Volume of Air.	
	Apparent.	True.	Solid Matter.	Air and Water (Pore Space).	In Normal Moist State.	After Period of Drought.[1]	In Normal Moist State.	After Period of Drought.[1]
Poor heavy loam (Rothamsted), loss on ignition, 4·3 per cent.	1·57	2·36	65·9	34·1	23·2	17·0	10·9	17·1
Heavily dunged arable soil (Rothamsted), loss on ignition, 10·0 per cent.	1·46	2·31	61·8	38·2	30·3	20·0	7·9	18·2
Pasture soil, loss on ignition, 13·0 per cent.	1·17	2·22	52·7	47·3	40·0	22·3	7·3	25·0

soils: it varies from 34 to 47 per cent., figures within the range of Schlichter's theoretical values. In laboratory experiments the pore space is increased by the presence of

[1] Driest periods of 1909 and 1910. During the abnormal drought of 1911 the numbers fell to 6 and 8 for the first two soils.

clay ; [1] in the field, however, this is not always true.[2] Pore space is also increased by the presence of organic matter, and it is higher in grass land than in arable, partly as a result of the actions of living organisms.

The space occupied by air at any time is calculated by deducting the volume of the water present from the total pore space, it being assumed that the volume of moist soil is the sum of the volumes of the solid particles and the water, an assumption, which, while not strictly true, is probably not far wrong. About 7 to 10 per cent. of the total volume of the Rothamsted soil is usually filled with air, the values ranging from about 25 per cent. down to very little.

In humid climates the air in the soil to the depth chiefly exploited by plant roots (6 or 9 inches) is almost identical in composition with that of the atmosphere, the two important differences being in the carbon dioxide and moisture content (Table 89).

Even the difference in carbon dioxide content is less than it appears, for the layers of air just above the soil contain more than the normal 0·03 per cent. of CO_2 where there is a dense cover of vegetation, as in woodlands or fields carrying heavy crops.

In arable soils the percentage by volume of oxygen usually exceeds 20·3, that of nitrogen is usually about 79, while the carbon dioxide varies from about 0·15 to 0·65 : the values for atmospheric air are respectively 20·96, 79·01, and 0·03. The chief variable, the CO_2, increases with the amount of organic matter in the soil and with temperature and moisture content ; it is higher in summer than in winter. It increases also when the crop is growing : H. W. Turpin [3] found in pot experiments 0·3 to 0·95 per cent. of CO_2 in the air of uncropped soils, but 0·3 to 2·0 per cent. in the air of cropped soils. In soils covered

[1] For illustrations see B. A. Keen and H. Raczkowski, *J. Agric. Sci.*, 1921, **11**, 441.

[2] O. W. Israelsen, *J. Agric. Res.*, 1918, **13**, 1.

[3] *Cornell Agric. Expt. Sta. Memoir* No. 32, 1920.

TABLE 89.—COMPOSITION OF THE AIR OF SOILS, PER CENT. BY VOLUME.

Soil.	Usual Composition.		Extreme Limits Observed.		Analyst.
	Oxygen.	Carbon Dioxide.	Oxygen.	Carbon Dioxide.	
Arable, no dung for 12 months	19-20	0·9	—	—	Boussingault and Lévy (1853).
Pasture land . .	18-20	0·5-1·5	10-20	0·5-11·5	Schloesing *fils* (1889).
Arable, uncropped, no manure, sandy soil	20·6	0·16	20·4-20·8	0·05-0·30	Lau,[1] mean of determinations made frequently during a period of 12 months. Values at depths of 15 cms., 30 cms., and 60 cms., not widely different. (30 cm. values given here.)
Arable, uncropped, no manure, loam soil	20·6	0·23	20·0-20·9	0·07-0·55	
Arable, uncropped, no manure, moor soil	20·0	0·65	19·2-20·5	0·28-1·40	
Sandy soil, dunged and cropped (potatoes), 15 cms. . . .	20·3	0·61	19·8-21·0	0·09-0·94	
Serradella, 15 cms. .	20·7	0·18	20·4-20·9	0·12-0·38	
Arable land unmanured	20·4	0·2	18·0-22·3	0·01-1·4	Russell and Appleyard (1915).
,, ,, dunged .	20·3	0·4	15·7-21·2	0·03-3·2	
Grass land . . .	18·4	1·6	16·7-20·5	0·3-3·3	

(Atmospheric air contains 21 per cent. of oxygen and 0·03 per cent. of CO_2.)

with grass, notwithstanding the greater pore space, the air contains more CO_2 (usually about 1·6 per cent. at Rothamsted), and appreciably less oxygen, usually about 18·4 per cent., but sometimes less than 17 per cent. at Rothamsted.

Headden [2] found a marked depression in CO_2 content of the air of soil carrying lucerne, after each cutting of the crop.

This increased CO_2 production on cropped land may contribute to the nutrition of plants by increasing the concentration of CO_2 in the lower layer of air in which the leaves are functioning.[3]

[1] *Inaug. Diss.*, Rostock, 1906.

[2] *Colo. Agric. Expt. Sta. Bull.* No. 319, 1927.

[3] P. Hasse and F. Kirchmeyer, *Ztschr. Pflanz. Düng.*, 1928, A, 10, 257.

Comparison of these values with the rates of production of CO_2 in soils shows that there must be a rapid exchange between the soil and the atmosphere. According to Romell's calculations, the air must be completely renewed every hour to a depth of 20 cms. when CO_2 is being generated at the recorded rate of 7 litres per square metre per day, or it could not remain at its normal composition. The cessation of the exchange for one and a half hours would double the amount of CO_2, while for fourteen hours it would increase the amount tenfold.[1] This rapid exchange is brought about partly by direct movement of streaming and partly by diffusion.

Several agencies cause a certain amount of direct movement. Changes in the atmospheric pressure, changes in temperature, movements of wind across the surface or of rain water through the soil all cause streaming of air in and out of the soil. E. H. Richards has shown [2] that rain brings down an appreciable amount of dissolved oxygen :—

DISSOLVED OXYGEN BROUGHT DOWN IN RAIN. RICHARDS.

	Average Rainfall (Inches) at Rothamsted (28 Years).	Dissolved Oxygen.	
		Parts per Million.	Lb. per Acre.
Summer .	13·32	9·0	27·12
Winter . .	15·50	11·2	39·27
Year . .	28·82	—	66·39

The aggregate effect of these weather conditions is sometimes sufficient to account for the hourly exchange ; indeed, some workers [3] attribute the whole effect to them. But the CO_2 content of the soil air shows no clear connection with barometric pressure or velocity of wind,[4] and both Russell and Appleyard's and Romell's investigations show that in

[1] L.-G. Romell, *Medd. Skogsförsöksanst.*, 1922, **19**, 125 ; 1928, **24**, 1.
[2] *J. Agric. Sci.*, 1917, **8**, 331.
[3] Mitscherlich (*Bodenkunde*, 1923), Hann, and others.
[4] E. J. Russell and A. Appleyard, *J. Agric. Sci.*, 1915, **7**, 1.

general these agents are insufficient to produce the observed effects; some continuously acting mechanism is necessary. Diffusion is therefore now regarded as being in all probability the chief factor in bringing about the exchange. The diameters of the soil pores are small, but, as H. T. Brown and F. Escombe have shown,[1] the rate of diffusion through small pores is not proportionately less than through larger ones;[2] it is governed rather by the total cross-sectional area of the pore space than by the size of the individual pores.

In spite of the rapidity of diffusion there appear to be local variations in the composition of the soil atmosphere. Leather obtained evidence that the amount of CO_2 is higher near plant roots than farther away. Localised activities of soil micro-organisms are probably accompanied by variations in CO_2 output, which, however, are difficult to demonstrate as the taking of even a small sample of soil air means extensive evacuation of the pores.

In natural conditions and in grass lands earthworms play an important part in aeration; their burrows make passages down which air and water can easily pass.

The importance of the soil air to the growing plant has led agriculturists to seek for methods of control. The most effective is to ensure a free passage to water capable of draining away, so that the pore spaces shall not be blocked; this is done by various drainage devices.

The various cultivation processes are commonly supposed to exert a great effect on soil aeration, and they certainly facilitate renewal of the soil air and increase the total volume of air in the soil by increasing the pore space. But experiments have shown no very striking reduction in the amount of CO_2 present: perhaps one could hardly expect this: if the air of an arable soil already contains as much as 20·3 per cent. of oxygen and as little as 0·3 per cent. of CO_2, there is

[1] *Phil. Trans.*, 1900, B, **193**, 223.

[2] For a full discussion see B. A. Keen, *The Physical Properties of the Soil* (1931).

little margin for improvement by cultivation, even by breaking the cap which forms after rain on a heavy soil. Yet the effect of tillage operations on plant growth is very marked, leading to a firm belief among farmers and gardeners that the soil aeration has been thereby perceptibly improved—a belief that deserves careful and unprejudiced examination by scientific workers.

The carbon dioxide in the soil atmosphere is not all that is present in the soil. Some is dissolved in the soil water, the exact amount depending on the other dissolved substances and the way in which the equilibrium with the soil air is affected by the presence of the soil colloids. Leather's calculations suggested large amounts of dissolved CO_2, but direct determinations would be desirable.

The nitrogen in the soil air was formerly supposed to be entirely inert: it is now regarded as the source from which the nodule organisms derive their supplies (p. 391). A crop of lucerne fixes about 1 cwt. per acre of nitrogen in three months, corresponding to about 10 c.c. per day per square metre of soil: the absorption of oxygen on the soils examined varies from about 2 to 26 litres per day (p. 343).

Below the dried mulch the soil air is more nearly saturated with moisture than the atmospheric air and the fluctuations in humidity are much less. This property is of obvious importance for the micro-organic life in the soil, since it minimises the effects of varying humidity and evaporating power known to exert a marked influence on life above ground.

Russell and Appleyard obtained evidence of a dissolved atmosphere in soil composed mainly of CO_2 and some nitrogen; presumably this is held by the soil moisture and the soil colloids. Its significance is that organisms needing anaerobic conditions can find them in normal soil provided they can tolerate CO_2.

In water-logged soils the air may contain much more CO_2 than in aerated soils and much less oxygen. A great change sets in when the oxygen disappears altogether. Marsh gas

and hydrogen are then formed (pp. 372, 405) neither of which is present in normal soil air to any greater extent than in the atmosphere.

So far we have been dealing with conditions in temperate and humid climates only. Leather's [1] determinations at Pusa suggest that the CO_2 in the soil air may be much higher, some of his values varying from 1 to 5 per cent., while the oxygen fell considerably; during the hot, dry season of April and May it was sometimes only 16 to 18 per cent., and during the rains (monsoon) of June and July it fell to 8 to 12 per cent. Others of his values, however, are not unlike those of temperate climates.

The Water Supply.

Of the water reaching the soil from the rain, part runs straight through the surface layers into the subsoil where it either remains or drains away, while the rest is held near the surface till it evaporates or is transpired by plants. In regions

TABLE 90.—RAINFALL, DRAINAGE, AND EVAPORATION FROM UNCROPPED LAND 20 INCHES DEEP. ROTHAMSTED, MONTHLY MEANS FOR 60 YEARS, 1870-1930.

Month.	Rainfall.	Drainage.	Drainage per Cent. of Rainfall.	Evaporation.
	Ins.	Ins.		Ins.
September	2·363	0·804	34·0	1·559
October	3·171	1·818	57·3	1·353
November	2·844	2·168	76·2	0·676
December	2·871	2·450	85·3	0·421
January	2·422	1·987	82·0	0·435
February	2·031	1·517	74·7	0·514
March	1·997	1·064	53·3	0·933
April	2·028	0·659	32·5	1·369
May	2·061	0·476	23·1	1·585
June	2·224	0·540	24·3	1·684
July	2·719	0·716	26·3	2·003
August	2·649	0·702	26·5	1·947
Year	29·380	14·901	50·7	14·479

[1] J. W. Leather, *India Dept. Agric. Mem.*, Chem. Ser., 1915, 4, 85.

of low rainfall the water does not penetrate far into the subsoil, and there is a lower depth sometimes called the dead layer which no water ever reaches. In humid regions there is normally drainage: the amount is greater in winter than in summer, and is higher on uncropped land than where vegetation is growing. The figures for uncropped land at Rothamsted are given in Table 90. About 75 per cent. drains away in winter, 25 per cent. in summer, and 50 per cent. on the average for the year.[1] On cropped land, however, the percolation is much less: in temperate regions of average rainfall about 25 to 30 per cent. :—

	Percentage of Rainfall Percolating through Soil.
Hertfordshire (Hemel Hempstead) [2]	21·8
Haute-Savoie [3]	26
Sweden, various places, average [4]	26
Germany,[5] N.E. region	29
Elbe Basin	28

The amount of drainage is really determined by the amount of evaporation, and this in turn is mainly determined by the temperature, so closely indeed at Rothamsted that, as Crowther [6] shows, the monthly values for drainage as set out in the table can be calculated from the equation—

$$D = 1{\cdot}920 + 1{\cdot}112R - 0{\cdot}0695T,$$

when D = drainage in inches,
R = rainfall in inches,
T = temperature in °F.[7]

[1] For Pusa results see H. N. Batham, *India Mem. Dept. Agric.*, Chem. Ser., 1926, **8**, 127, and for a statistical examination of the Punjab irrigation results see B. H. Wilsdon and R. P. Sarathy, *Punjab Irrig. Res. Lab. Mem.* No. 2, 1928,

[2] J. Evans, *Proc. Inst. Civil Engineers*, 1876, **45**, 1478.

[3] Risler (1867-1876) quoted by A. Demolon, *La Dynamique du Sol*, Paris, 1932, p. 162.

[4] H. Flodkvist, *Sverig. Geol. Unders.*, Ser. C, 1931, No. 371; Årsbok, **25**, No. 4.

[5] J. Rothe, *Ztschr. Pflanz. Düng.*, 1930, B, **9**, 512.

[6] E. M. Crowther, *Proc. Roy. Soc.*, 1930, B, **107**, 1.

[7] The numerical values are for the period 1878-1928.

Drainage from heavy soils is mostly through the cracks, but from light soils through the pore spaces.

The water retained in the surface layers, like the soil air, is held in the pores, and the volume of pore space sets the limit beyond which its amount cannot increase, and which, indeed, in nature it rarely attains. The quantities usually present vary with the different types of soil, as shown in Table 91 :—

TABLE 91.—MOISTURE CONTENT[1] OF SANDY, LOAMY, AND CLAY SOILS AT WOBURN LYING NOT FAR APART, AND UNDER APPROXIMATELY EQUAL RAINFALL CONDITIONS. RUSSELL.

	Sandy Soil (Clay = 5·0 per Cent.).	Loamy Soil (Clay = 9·3 per Cent.).	Clay Soil (Clay = 43·0 per Cent.).
Highest observed .	14·0	16·5	35·0
Lowest observed .	1·1	6·0	15·8
Mean of all observations	9·0	12·0	27·0

They are highest and least liable to fluctuations in clay and peaty soils, and lowest and most liable to fluctuations in sandy and chalky soils.

The older investigators recognised several differences in the relations of soil water to the growing plant. Water-logged soils in which water completely fills the pore space are unsuited for all except marsh plants including a few crops like rice. At the other extreme the so-called " air dry moisture " retained by the soil after prolonged drying in air is quite unavailable to growing plants: indeed Heinrich[2] showed long ago that they wilted at a moisture content higher even than that attained by the dry soil in a saturated atmosphere (the hygroscopic coefficient of Hilgard). His determinations of the water contents of soil illustrate the differences for different soil types :—

[1] This determination was made by drying at 40° C.

[2] *Jahrb. Agric. Chem.*, 1875-1876, p. 368.

WATER CONTENT CALCULATED AS PER CENT. OF DRY SOIL.

Kind of Soil.	Coarse Sandy.	Sandy Garden.	Fine Humus.	Sandy Loam.	Calcareous.	Peat.
When plants wilted .	1·5	4·6	6·2	7·8	9·8	49·7
Hygroscopic coefficient .	1·15	3·0	4·0	5·7	5·2	42·3

In natural conditions the store of water in the soil that is available to the growing plant is the quantity between this limiting amount where wilting occurs, and an upper limit representing the amount the soil can hold against free drainage.

Hilgard (1906) in California was one of the first to develop this subject, and he made extensive studies of the amounts of water different soils could hold and supply to the plant. He divided the soil water into three kinds :—

(1) Hygroscopic moisture, a film of condensed water vapour, held with very great force and incapable of movement as liquid, and not available to plants.

(2) Capillary water, held in the pores by forces greater than gravity so that it does not drain away.

(3) Gravitational water held much more lightly so that it can drain away.

Briggs (1897) was the first to see clearly how the curvature of the air-water menisci determines the amount of water that the soil can retain in equilibrium against gravity. In studying the water-holding power of soils Briggs and McLane (1907) attached particular importance to the "moisture equivalent," the amount of moisture held by a soil after centrifuging in a cup with a porous base at a known speed, *i.e.* held against a known force : they adopted a force of 1000 times gravity. Briggs and Shantz (1912) allowed plants to reduce the moisture content of soils in impervious containers until a point was reached when they not only wilted when allowed to transpire freely, but would not recover in a saturated atmosphere unless water was added to the soil.

This limiting moisture content appeared to be largely independent of the plant but characteristic of the soil; hence they spoke of it as the "wilting coefficient" of the soil. Using a group of soils from the Great Plains of North America, they determined its regression on the "hygroscopic coefficient," on the "moisture equivalent," on Hilgard's "maximum moisture" (the moisture retained in a small mass of saturated soil after drainage), and on the mechanical analysis, thereby obtaining average factors for calculating the wilting coefficient.

Two factors determine the availability of the soil water for the plant:—

(1) The respective pulls or suction pressures exerted by the plant and the soil.

(2) The ease with which water can travel in the soil to replace what has been taken up by the roots.

Some estimate of the suction pressure exerted by the plant root is obtained from a knowledge of the osmotic pressure of the root sap. For most plants this is in the neighbourhood of 20 atmospheres when the soil moisture is nearing the wilting coefficient.[1] Somewhat higher values are found in certain desert plants even in salt-free soil, while many plants can develop considerably higher pressures in saline conditions. For *Atriplex concertifolia* a pull equivalent to 153 atmospheres has been recorded, while Faber has measured in the mangrove *Avicennia* a pressure of 163 atmospheres in the leaves, and 96 atmospheres in the roots (p. 44).

In view of these differences it is clear that the wilting-point is not quite the same for all plants, and one cannot speak strictly of a wilting coefficient. For a wide range of plants,

[1] See E. Hannig, *Ber. Deut. Bot. Ges.*, 1912, **30**, 194 (7 to 8 atmospheres); H. H. Dixon and W. R. G. Atkins, *Proc. Roy. Dublin Soc.*, 1913, **13**, 434. Some of their results are: Roots of *Beta vulgaris* up to 21·2 atmospheres; of *Ilex aquifolium*, 7·64 to 15·7 atmospheres; of *Helianthus tuberosus*, 13·5 atmospheres.

For further information see F. J. Molz, *Amer. J. Bot.*, 1926, **13**, 433 and 465.

however, and excepting only the extreme types, the wilting-points do not vary much, and for practical purposes can be regarded as almost constant,[1] though for a series of soils they are not closely related either to the hygroscopic coefficient or the moisture equivalent.

The Suction Pressure of the Soil.—Numerous investigations have shown that the suction pressure with which a soil

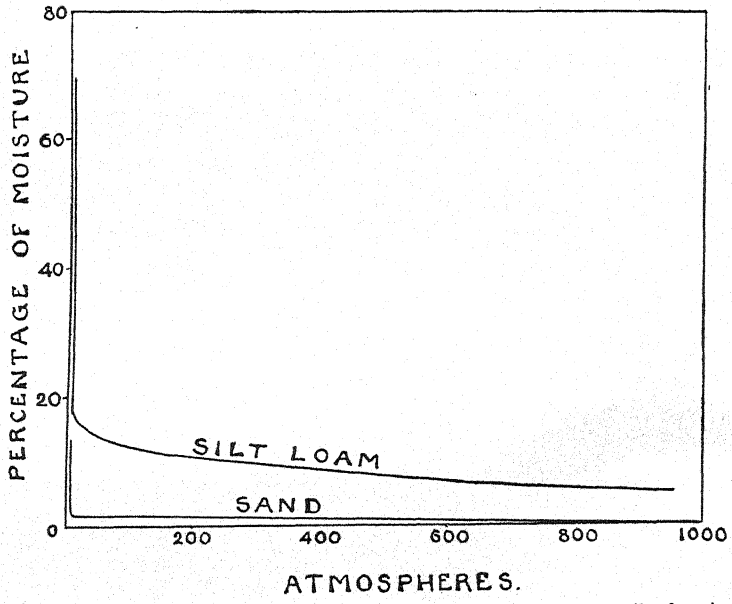


FIG. 52.—Magnitude of force with which water is held by soil, showing change with decreasing water content (C. A. Shull, *Bot. Gaz.*, 1916, **62**, 1).

withholds its water varies rapidly with changes in its moisture content. Freezing-point determinations were made by G. Bouyoucos and vapour pressure measurements by M. D. Thomas: from both sets of data it is possible to trace connections between suction pressure and moisture content. Shull used suction by xanthium seeds to study the variation

[1] F. J. Veihmeyer and A. H. Hendrickson, *Plant Physiol.*, 1928, **3**, 355; H. A. Wadsworth, *Hawaii Plant Rec.*, 1934, **38**, 111.

in the soil suction with soil moisture content (Fig. 52). A. F. Lebedeff [1] measured the percentage of water retained by the soil when subjected to centrifugal forces of various magnitudes up to 70,000 times gravity (Fig. 53). Owing to the complexity of the conditions in the centrifuge the moisture contents can only be very approximately related to the corresponding suction pressures.

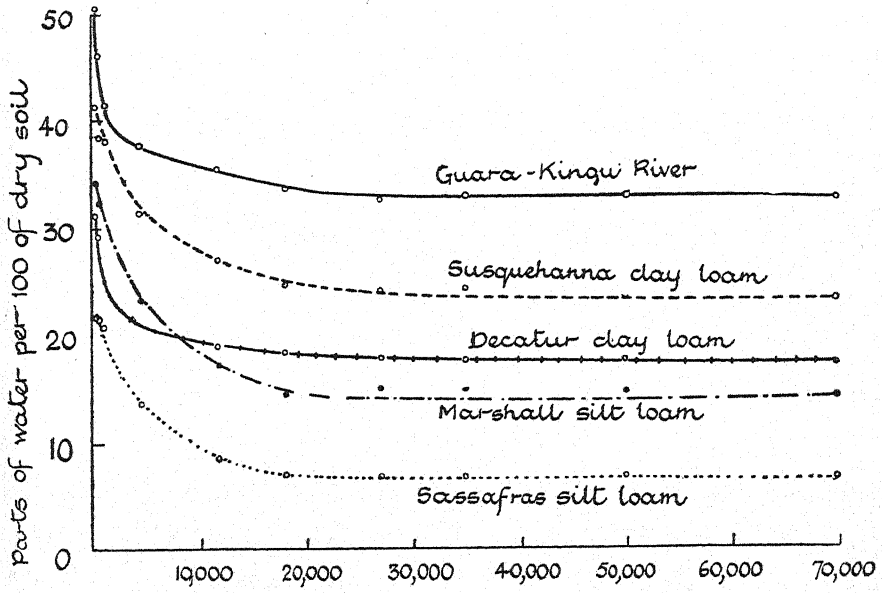


FIG. 53.—Water held by soil against increasing centrifugal force measured in terms of g (A. F. Lebedeff).

R. K. Schofield [2] has recently put the whole subject on a sound basis by reducing the measurements made in different ways to a common basis, using a scale which he calls pF. He has been able to express quantitatively Keen's view that the hygroscopic coefficient, wilting coefficient, moisture equivalent, etc., are merely particular points on a smooth curve,

[1] *Proc. 1st Int. Cong. Soil Sci.*, Washington, 1927, **1**, 551. He worked up to 50,000 revolutions per minute, corresponding to a force of 70,000g.

[2] *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **2**, 37.

and that "hygroscopic" and "capillary" water are not sharply differentiated but merge imperceptibly one into the other.

The pF Scale.—When wet soil is placed in an atmosphere of fixed relative humidity (*h* per cent.), evaporation continues until the moisture content has been reduced to a value which depends on the nature and previous moisture history of the soil sample and on *h*. When evaporation ceases, the free energy of the water remaining in the soil is less than that of pure water in bulk by $\frac{RT}{18} \log_e \left(\frac{100}{h}\right)$ ergs per gram. If this free energy difference is divided by *g* it becomes expressed as the height in centimetres of a column of water that corresponds to the "suction" with which the remaining water is retained; or the effective height above a free water-table. Evaporation into a 50 per cent. relative humidity atmosphere develops a suction in the remaining water equivalent to 1,000,000 cm. of water, a column higher than Mount Everest. On the other hand, drainage to a water table develops suctions of the order of 1000 cm. and less.

The difficulty of comparing such widely different figures has been met by using the logarithms of these figures. By analogy with Sørensen's logarithmic acidity scale, the symbol *p*F has been used (F being the recognised symbol for free energy).[1]

There are great experimental difficulties in the way of measuring evaporation into atmospheres more humid than about 95 per cent. saturation; and 60,000 cm., or *p*F 4·78, the suction developed by evaporation into an atmosphere over 10 per cent. sulphuric acid (95·6 per cent. relative humidity), is about the lowest value obtainable in this way. On the other hand, the highest value obtainable by vacuum suction through a filter is 1000 cm., or *p*F 3. These two methods, therefore, are insufficient to deal with the whole range of soil suction: the region between *p*F 3 and *p*F 4·8 is not covered by them.

[1] The *p*F is thus the logarithm of Buckingham's "capillary potential."

Fortunately, freezing-point determinations enable this gap to be bridged. A freezing-point depression (t) of 1° C. corresponds to pF 4·1 or a suction of 12,700 cm. of water; Schofield expresses the relation thus :—

$$p\mathrm{F} = 4{\cdot}1 + \log_{10} t.$$

Schofield and J. V. B. da Costa[1] have studied the range extending from the wilting coefficient to the maximum quantity the soil can retain under conditions of good drainage.

They traced the curves connecting pF with moisture content for a number of soils for which the Briggs and Shantz "wilting coefficient" had been determined, and found that in every case the pF corresponding to the "wilting coefficient" lay between pF 4·0 and pF 4·4, although the corresponding moisture contents ranged from 2·9 to 21·6 per cent. of dry soil. Taking the mean value of pF 4·2 and reading the corresponding moisture content from the curves plotted from the freezing-point measurements, the values obtained differed on an average by only 0·7 per cent., from the moisture contents found in the wilting experiments. The greatest difference was only 1·2 per cent., which would be of small consequence in field measurements.

The rapidity with which the suction pressure changes with moisture content in the neighbourhood of the wilting coefficient is apparent from these curves. A change of only 1 to 2 per cent. in the moisture content may double the amount of suction.

The mean value, pF 4·2, for the wilting coefficient agrees closely with the values calculated by Schofield's formula

$$p\mathrm{F} = 6{\cdot}5 + \log_{10}(2 - \log_{10} h)$$

from the relative humidities (h), 99·88 per cent. and 99·83 per cent., found respectively by M. D. Thomas and Edlefsen by measuring the aqueous vapour pressure of soil dried to the wilting coefficient. In so far as comparison can be made, it

[1] *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, 1, 6.

also agrees with Lebedeff's measurements (Fig. 53). The corresponding suction pressure of 16,000 cm. (16 atmospheres) is of the order of magnitude expected from cryoscopic measurements on plant sap, and it agrees closely with the osmotic pressure of a culture solution which Veihmeyer found just caused the permanent wilting of young sunflower plants when transferred to it from sand culture. These measurements were all made with non-saline soils (salts less than 500 parts per million of dry soil). Plants that can grow under saline conditions appear to be able to increase the osmotic pressure of their cell sap to a considerable extent by taking in some of the salts.

The various coefficients proposed by different workers for estimating the upper limit of water supply in the soil can also be given exact or approximate *p*F values. Thus the average value in a Hilgard and Keen-Raczkowsky box, when the soil initially saturated has just finished draining, is about *p*F 0; the moisture equivalent is roughly at *p*F 3. Working down to drier conditions the wilting coefficient is as above stated about *p*F 4·2, the air-dry state is close to *p*F 6 and the oven-dry state nearly *p*F 7.

The figures set out above relate to soil that is losing water. Soil that is gaining water gives a different set of values. This is true for all properties connected with the moisture content of the soil: two sets of values are obtained for any particular moisture content according as the soil is becoming wetter or becoming dryer. The suction needed to withdraw water from a moist soil is greater than that against which water will enter the soil at the same moisture content (Fig. 54). Of the wetting coefficients the most important are the "hygroscopic coefficient" of Hilgard and the "hygroscopicity" of Mitscherlich determined by allowing dry soils to take up as much water vapour as they can under definite conditions. Hilgard used a saturated atmosphere, but Puri and others have shown that this leads to arbitrary results. Mitscherlich stands the soils over 10 per cent. sulphuric acid (*p*F 4·78).

The lack of similarity in shape of the *p*F curves of different soils accounts for the breakdown of Briggs and Shantz formula for calculating the wilting coefficient.

Maximum Water Supply in the Soil.—In irrigation practice it is highly important to know how much water should be

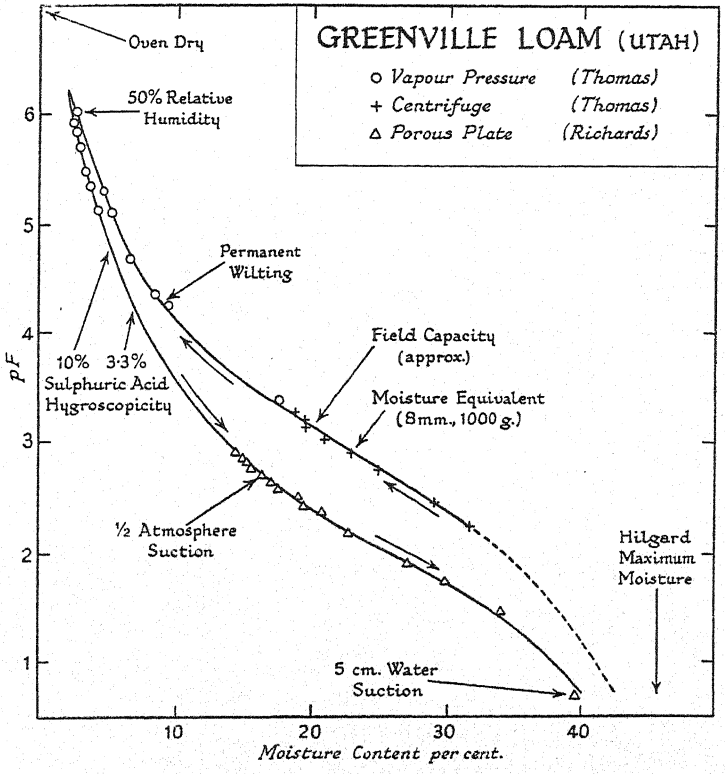


FIG. 54.—Relationship between *p*F and moisture content for a loam (Schofield).

given to a soil without overstepping the maximum that the soil can hold. Any excess is at best wasted by seepage, and frequently it may cause serious damage to lower lying land.

Field Moisture Capacity.—Observations on the manner in which irrigation water is distributed in the soil within a day or two of its application suggest that the quantity of water

a soil can retain after being wetted and allowed to drain is fairly definite; it is called the "field moisture capacity." Moreover, when the soil has been dried to a considerable depth by root action a limited application of water does not moisten the whole of the dry zone, but remains in a layer just deep enough to have its moisture content raised to the neighbourhood of the field moisture capacity; the soil below this is scarcely affected. The field moisture capacity is commonly not very different from the moisture equivalent determined in the Briggs-Maclean centrifuge.[1] After the empirical factor for the area has been determined the field moisture capacity of particular fields can be estimated sufficiently closely from the moisture equivalent.[2]

Knowing the approximate depth of root range it is then possible from a simple determination of the soil moisture content to calculate how much additional water is needed to moisten the soil mass to its full capacity so far as the roots extend but no further. Waste can therefore be reduced to a minimum. This method of control is much used in California.

The "field moisture capacity," however, while practically very useful, is not a definite constant. Burr[3] in Nebraska and Israelsen[4] in Utah find that after heavily irrigating a soil and then protecting it from evaporation by a thick layer of straw the top 12 feet continued to lose water by slow drainage long after the two to six days usually allowed for the determination of field moisture capacity. Between the eighth and the thirtieth day after a 36-inch irrigation the top 6 feet lost 3 to 4 inches of water, and approximately another inch was lost during a further period of several months.

[1] For details of procedure see F. J. Veihmeyer, O. W. Israelsen, and J. P. Conrad, *Calif. Agric. Expt. Sta. Tech. Paper* 16, 1924.

[2] Bouyoucos recommends the use of an ordinary Buchner suction filter in place of the centrifuge (*Soil Sci.*, 1935, **40**, 165).

[3] *Nebr. Agric. Expt. Sta.*, 23*rd Ann. Rept.*, p. 93.

[4] *Hilgardia*, 1927, **2**, 509.

Movement of Water in the Soil.—The absorption of water by plant roots leads to considerable inequalities in the distribution of water in the soil, and much work has been done to discover the mechanism by which redistribution can take place. According to the older view, developed fully by Briggs (1897), capillary forces caused the water to move round the particles in films, and so long as these remained unbroken they rapidly readjusted the water content. This simple idea has had to be abandoned.

It is now recognised that capillarity is related to the pore spaces between the particles, and not to the particles themselves. The complex relationships of pore space and capillary films have been studied in detail by Haines.[1] He shows that the pore space in soil must be regarded as cells communicating with each other through relatively narrow necks, and that, in general, a change of moisture content at any point in the soil proceeds not in a smooth, continuous manner but relatively abruptly, by the sudden emptying or filling of a cell. This type of movement is a joint consequence of the geometry of the pore space and the physical properties of curved water films.

A further consequence is that changes in moisture content are not, in the main, strictly reversible, but fall into two series corresponding to the directions of increasing and decreasing moisture content: the curve connecting moisture content with progressive changes in the equilibrium conditions in the curved water film is not a single one but a loop; one branch refers to increasing moisture content, the other to decreasing moisture and the complete cycle is known as the hysteresis loop.

These new conceptions, the referring of the water film to the pore space instead of to the particle, and the recognition

[1] For details and references see B. A. Keen, *Physical Properties of the Soil*, 1931, in which a full account is also given of the attempts of W. H. Green and G. A. Ampt to apply Poiseuille's equation to soil and of E. Buckingham and W. Gardner to develop the analogy between the movement of soil moisture and the flow of heat and electricity.

of colloidal properties and of hysteresis and the many consequences following therefrom, have completely changed the whole idea about capillarity. As a way of holding water up in the soil against loss of gravity, capillarity is recognised as a potent force, but as a mechanism for distribution of water in a soil it has lost much of its old importance.

It has been a matter of great difficulty to determine how far and how fast capillary movement will occur upwards and sideways to make good local moisture deficiencies caused by root action and surface evaporation.

Determinations of the water content of the soil have shown rapid losses close to the surface, but considerably smaller losses below. Keen [1] measured the level of standing water in impervious cylinders full of soil, and found that, after the soil had been saturated by rain, the level fell rapidly during the first few days of dry weather, but very slowly afterwards : the fall was extremely slow by the end of a three months' drought. Veihmeyer made a somewhat similar experiment. He determined during a summer drought the losses of weight of a large tub filled with a medium loam at field moisture capacity ; the loss at first was rapid, but even after three months it amounted only to about 2 inches of water.

In studying the influence of ground water level on the vegetation in the Dutch dunes, Bijl [2] showed that the growth of grass was good when the water level was maintained at 12 inches (30 cm.) below the surface, but poor when the level fell to 20 inches (50 cm.) ; it failed altogether when the fall went further to 24 inches (60 cm.) On arable land the most favourable depth of the ground water was 20 inches (50 cm.). If the depth were 32 inches (80 cm.) crops were uncertain : if it were 40 inches (100 cm.) they failed.

The chief movement of water in the soil is the downward movement that takes place under the influence of gravity.

In general it appears that water travels through the pores

[1] *Proc. 1st Int. Cong. Soil Sci.*, Washington, 1927, I, 504.
[2] I. J. G. Bijl, *Het grondwater in Rijnland*, Rotterdam, 1930.

of sand and silt soils, but down the cracks in clay soils. Evidence of this is afforded by inspection of the face of a fresh cutting, say 4 or 5 feet in depth. The clay is found to break easily into leaves or plates the faces of which show red or brown stains left by the iron or manganese dissolved in the water; if the clay is permanently water-logged the stains are greenish, and they may look completely green until one breaks the lump, when its proper brown colour appears.[1]

Growth of Plant Roots in a Drying Soil.—If the water cannot move to the plant, the roots can in suitable conditions grow quickly enough to keep touch with a slowly moving water supply.

In the Kassala region of the Sudan, for instance, cotton is sown at the end of the flood season while the silty soil is still saturated with water. Although there is no rain throughout its whole period of growth it germinates and grows, developing a root system that strikes deeper into the soil as the surface layers become dry, and supplying the plant with sufficient water to allow of satisfactory growth. The writer has seen the mature plants at midday under a scorching sun showing no signs of wilting. In a less striking way the same phenomenon is shown by lucerne: once established it can become almost independent of rainfall: it will send its roots in favourable conditions even 20 feet into the soil.

Differences in power of doing this are an important factor in the competition between plants.[2]

Movements of water and root growth are both easy in medium loams, so that plants growing on them suffer less from drought or heavy rainfall than those growing on other soils. On the other hand, roots develop and water moves with greater difficulty in heavier soils: a sharp line usually separates

[1] For a good laboratory demonstration see C. S. Slater and H. G. Byers, *U.S.D.A. Tech. Bull.* No. 232, 1931.

[2] See V. T. Aaltonen, *J. Forestry*, 1926, **24**, 627, and J. W. Toumey and R. Kienholz, *Yale Univ. School of Forestry Bull.* No. 30, 1931.

the dried-out upper layer of soil from the moister one below; indeed in hot, rainless weather, a clay soil may be cracking with drought only a few feet away from a stream.

Loss of Moisture by Evaporation.—Numerous experiments have been undertaken to determine the amount of moisture lost by evaporation from a bare soil, principally to ascertain how far moisture can be accumulated and stored during a period of bare fallow for the use of the next crop.

Burr [1] showed that at the end of the summer at North Platte (Nebraska), bare tilled land contained some 5 inches more moisture in the top 6 feet than land that had just carried a wheat crop; this difference persisted throughout the rainless winter and considerably benefited the succeeding crop. The loss from the light soils is somewhat less than that from the heavier. E. C. Chilcott,[2] summarising numerous experiments in the Great Plains area of the United States, concluded that the amount of moisture conserved by bare fallowing was not increased by doing more cultivation than is necessary to kill the weeds. Subsequent experiments have, in the main, confirmed this, although earlier investigators thought that evaporation was checked by loosening the top inch or two of soil and so forming a mulch to break the supposed capillary tubes.

The Temperature of the Soil.

The soil derives its heat almost entirely from the sun, the small amounts due to oxidation of organic matter and to radio-activity being, so far as is known, negligible in influencing plant growth. The temperature of the soil depends, therefore, on the amount of heat received by the surface and the way in which this heat is used.

Soil can receive or lose heat by three separate processes: by radiation; by convection, the warming or cooling due to

[1] *Nebr. Agric. Expt. Sta. Bull.* No. 114, 1910.

[2] *U.S.D.A. Bull.* No. 268, 1915; see also Nos. 1173, 1287, 1293, 1301, 1310, and 1315 (various authors).

movements of air and water ; and by condensation or evaporation of water. Radiation is, however, the most important. The quantity of radiant energy received depends on the quantity reaching the earth, which varies from time to time ; on the opacity of the atmosphere ; the topographical position and the vegetation cover of the soil.

The atmosphere absorbs an appreciable fraction of the radiant energy but not all kinds alike.

The upper atmosphere absorbs the short wave ultra-violet radiation very strongly, but transmits most of the longer visible and infra-red heat waves. These are readily transmitted also by dry air in the lower atmosphere, but much less readily by carbon dioxide and water vapour. The actual absorption by carbon dioxide is not large because of its low concentration in the air ; the absorption by water vapour and particularly by condensed water in the form of clouds and mists may be considerable.

Two distinct factors in the topographical position of a soil affects the quantity of radiation it receives : the thickness and composition of the atmosphere, and the angle at which the radiation strikes the soil surface. At high altitudes in arid deserts where the air is very dry, or in the tropics when the sun passes overhead, the atmosphere absorbs much less radiation than in high latitudes or in the evenings and mornings when the rays of the sun fall very obliquely on the earth's surface, and so must traverse a great thickness of absorbing atmosphere.

In natural conditions the rays reaching the surface do not all penetrate the soil. Many may be intercepted by vegetation, consequently land densely covered by plants is cooler than bare land ; advantage is often taken of this fact in tropical countries to protect soil from intense evaporation by the growth of "shade" crops. Of the radiant energy finally reaching the surface, an unknown fraction is reflected back again into space ; probably more from a white chalky soil than from a black humus soil.[1]

[1] See Firbas, *Beih. Bot. Cbl.*, 44, 179, for some consequences of this.

The amount of energy received on a horizontal surface at Rothamsted averages per square centimetre per week about 250 small calories or 1000 Joules in the winter-time; about 3500 calories or 15,000 Joules in the summer-time; and about 2500 calories or 10,000 Joules over the growing period, March to September. The variations from season to season are mainly due to cloud, for when the data for cloudless days are collected and joined up the curve is seen to be substantially the same each year [1] (Fig. 55). Broadly speaking, the total radiation received on each acre of land at Rothamsted during

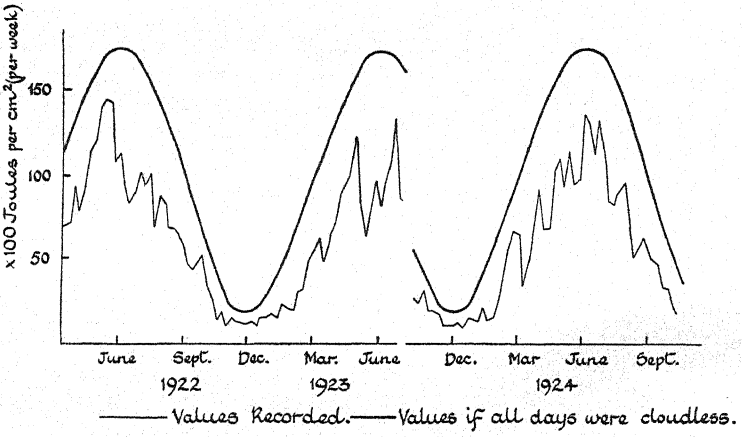


FIG. 55.—Solar radiation received at Rothamsted, 100 Joules per sq. cm. per week. Lower line: actual values; upper line: smoothed curve for cloudless days.

the growing period, March to September, is about $2{\cdot}5 \times 10^{12}$ calories or 10^{10} British thermal units.[2]

[1] W. B. Haines, "A Comparison of the Radiation Recorders at Rothamsted," *Quart. J. Roy. Met. Soc.*, 1925, **51**, 95; the relations with hours of sunshine are discussed. The surface is enclosed in an evacuated glass bulb and the record is made by the Callender Recorder of the Cambridge Scientific Instrument Company. 1 calorie (small calorie) = 4·2 Joules and 1 Joule = 10^7 ergs.

[2] This equals nearly 3 million Board of Trade electrical units, or 4 million h.p. hours: it is equivalent to the heat developed by burning some 350 tons of coal and would bring 25,000 tons of water from the freezing to the boiling-point. Only about 0·5 per cent. of this is recovered in the crop.

These values are for a horizontal surface; for inclined surfaces they would be different by amounts easily calculated. A surface at right angles to the sun's rays at midday receives more heat than an equal area sloping any other way; a south slope in our latitude is warmer than a north slope, often by several degrees, sufficient to produce marked vegetation differences.

The soil not only gains, but also loses, heat by radiation. This loss is controlled by the atmosphere, by the vegetation, and by the rate at which the surface of the soil can be supplied with heat from the subsoil. A clear, dry atmosphere absorbs very little of the heat radiated by the soil, but if it contains much water vapour it acts like a blanket and prevents much loss. Thus on clear nights bare soil can radiate much more heat than on clouded nights: similarly desert soils can radiate much more heat than soils in more humid climates.

Of the radiation falling on the soil, part is absorbed and part reflected. The part absorbed raises the soil temperature by an amount depending on the specific heat of the soil and the rate of conduction of heat from the surface. The specific heat depends on the moisture content and varies from about 0·2 for a dry soil to about 1 for a very wet soil. The rate of conduction depends both on the moisture content and on the tilth. A dry soil is a very bad conductor of heat, especially if it is in fairly fine crumbs, for as the crumbs touch only at points they exchange energy mainly by radiation or by air convection. But if the soil is damp, water films form round the individual soil particles and increase the thermal conductivity. Thus the surface of a dry soil warms much more quickly than that of a wet soil and may indeed on sunny days [1] be hotter than the air.

[1] This is well seen on sand dunes where the air temperature just above the sand may be 5°-10° C. higher than that of the air generally. The phenomena are well marked in hot climates. Leather (*India Dept. Agr. Mem.*, Chem. Ser., 1914, **3**, 15) states that the maximum temperature at Pusa may rise to 70° C. at the soil surface and to 50° at the depth of 1 to 2 inches, the air temperature also being about 50° C. E. McKenzie Taylor

The temperature waves in the soil are thus damped down ; if the soil is dry the thermal conductivity is reduced so that heat is transferred but slowly ; if the soil is wet the specific heat is high, so that, although heat can be transferred more readily, more of it is required to raise the soil temperature by a given amount. Since the daily heat wave travels only slowly it does not get very deep before reversal takes place. Thus at Rothamsted the maximum temperature is commonly attained in the air about 2.15 p.m., but at 6 inches depth in the soil not till 5.30 p.m. This time-lag is less in wet and greater in dry weather. Owing to the damping of the temperature wave, fluctuations in air temperature of less than 2° C. are often inappreciable in the soil at 6 inches depth. Fig. 56, from Keen and Russell, shows some typical curves obtained at Rothamsted for the air temperature taken in the screen and the soil temperature at 6 inches depth. In general the soil temperature curve resembles the air temperature curve except that it is very much smoother. The soil minimum usually lies above the air minimum, while the soil maximum, although it usually lies below the air maximum, yet may lie above it, especially in summer and early autumn. In winter time the soil curve is often flat for a whole day and sometimes shows practically no variation for several days on end.

The general result of all these interactions is that—

(1) A south slope is warmer than a north slope.

(2) Bare land is warmer than land covered with vegetation, excepting during winter months, and has a larger daily variation in temperature.

(3) The surface of a soil exposed to the sun's rays is often hotter than the air, and is subject to considerable temperature variations.

and A. C. Burns recorded 65° C. at the surface, and over 56° at a 2-inch depth at Giza, near Cairo (*Min. Agric. Egypt Bull.* No. 31, 1924). P. A. Buxton describes a simple device for recording surface temperatures in hot climates : a set of waxes differing each about 2° in melting-point from its neighbour is used : shavings are dropped on to the soil (*J. Ecology*, 1924, **12**, 127.

(4) These variations, however, only slowly affect layers 3 or more inches below the soil; they also become rapidly narrower, and at a depth of 6 inches they are much less than those of the air temperature.

(5) Moist soil, being a better conductor than dry soil, is more uniform in temperature throughout its depth.

(6) The top 6 inches of soil has a higher mean temperature than the air both in summer and in winter. At 6 inches the warmer part of the day centres round 5.30 p.m., and the cooler part round 9.30 a.m.

(7) The warming of the soil in spring is facilitated by drying; the cooling in autumn is increased by clear nights and diminished by rain.[1]

Records extending over periods of some months have been published by Wollny [2] and by Thiele.[3] British data generally refer only to 6-inch or 12-inch readings; they have been collected and worked up by Mawley, by Mellish,[4] and by Franklin.[5] Systematic readings are taken at the Radcliffe Observatory, Oxford,[6] at Kew, and also at Rothamsted, where a continuous self-recording thermometer is installed. Detailed records of soil temperatures at East Lansing, Mich., have been taken by Bouyoucos [7] who has also discussed their effect on the physical properties of the soil.

Some degree of control of soil temperature [8] is exercised by farmers and cultivators. The most effective way of raising the temperature is to remove some of the water; draining a water-logged soil often leads to striking increases. A second method, more frequently applicable, is to lay the soil in ridges,

[1] Keen and Russell, *J. Agric. Sci.*, 1921, **11**, 211.

[2] *Forsch. Geb. Agrik.-Physik.*, 1878, **1**, 43; 1881, **4**, 327.

[3] *Landw. Vers.-Sta.*, 1905, **63**, 161.

[4] See *Quart. J. Roy. Met. Soc.*, 1899, **25**, 238.

[5] *Proc. Roy. Soc.*, Edin., 1919, **40**, 10 and 56.

[6] See A. A. Rambaut, *Radcliffe Observations*, 1901, **48**, 1, and 1916, **51**, 103; also *Phil. Trans.*, 1901, A, **195**, 235.

[7] *Michigan Tech. Bull.* No. 17, 1913; Nos. 22 and 26, 1916.

[8] For discussion of the ecological significance of soil temperature variations see H. Lundegårdh (1925).

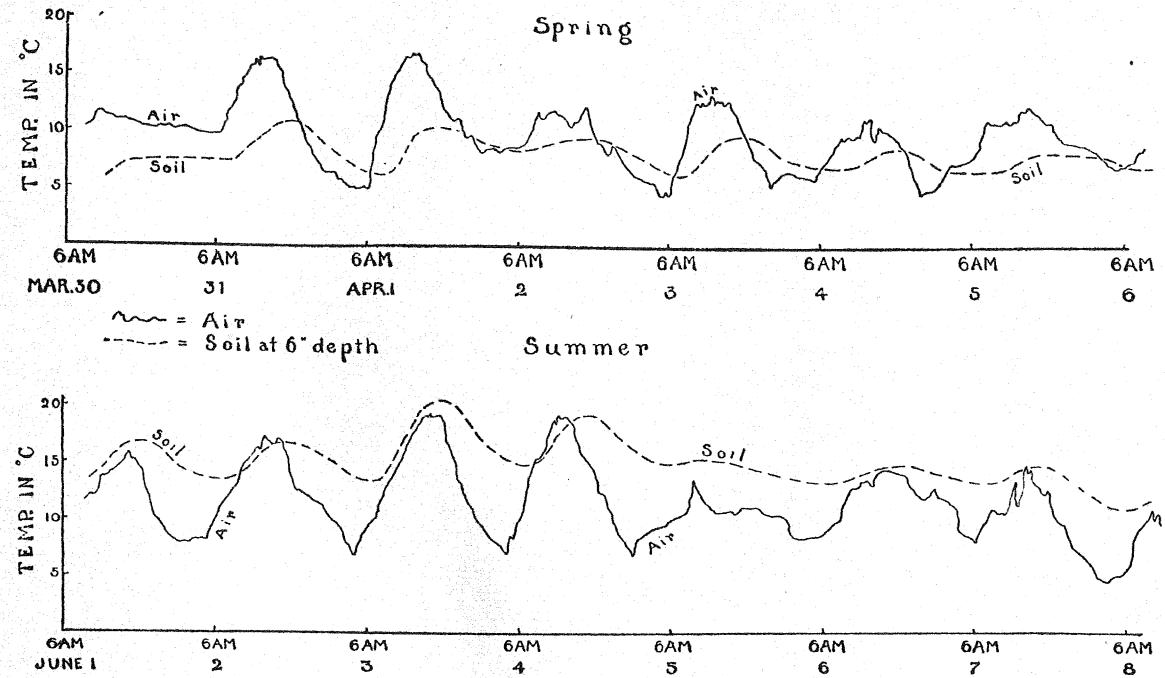


FIG. 56.—Soil temperatures in spring and summer taken by a continuous recording thermometer embedded 6 inches in bare ground at Rothamsted (Keen and Russell).

if possible running east and west; the south face of the ridge thus becomes warmed. The total heat received by the field is of course not increased, but it is concentrated on part of the land.

Lowering of the soil temperature is often desirable in hot countries or during dry summers. It can be accomplished by irrigation or by maintaining on the surface a layer of loose dry earth which, being a non-conductor, shields the underlying soil from the sun's rays (Table 92) :—

TABLE 92.—TEMPERATURES OF SOIL AT DIFFERENT DEPTHS UNDER VARYING CONDITIONS. RUSSELL.

Effect of Weather.

	Air Temp.	Temperature of Bare Soil.					
		Untouched.			Surface Stirred by Hoes.		
		½ inch.	3 inch.	6 inch.	½ inch.	3 inch.	6 inch.
Hot sunny day, 20th June, 1910	30°	35°	30·5°	27°	31·5°	29·8°	26·5°
Cold cloudy day, 27th June, 1910	18°	17·5°	16·7°	15·8°	17°	16·3°	15·5°

Effect of Vegetation.

	Warm Weather, 5th Oct., 1910, Air Temperature, 17°.			Cold Weather, 4th Jan., 1911, Air Temperature, 3·5°.		
	½ inch.	3 inch.	6 inch.	½ inch.	3 inch.	6 inch.
Bare soil	17°	16·7°	15·5°	3°	2·5°	2·5°
Soil covered with living vegetation (grass land) . . .	15·5°	15°	14·5°	3°	3°	3°
Soil covered with dead vegetation (mulched land) . .	15·5°	15°	14·5°	2·5°	2·0°	2·0°

Soil Tilth.

The fine crumbly soil structure known as a good tilth is the best suited for plants; it is associated with good water and air supply and easy penetration for the roots. The sticky lumpy state is unsuited for plants; the air supply to the roots is inadequate; so, often, is the water supply; while the roots themselves are unable to move far into the soil, so that the

natural vegetation is restricted to plants possessing a surface habit of growth like *Agrostis*, or others such as coltsfoot with large thick roots of great penetrating power.

Soil Aggregates[1] and Soil Tilth.

The crumb structure of soils in good tilth possesses the following properties :—

(1) It allows the plant roots an optimum air and water supply.

(2) It resists the shattering action of wind, rain, and cultivation implements, and remains stable when wet.

The ideal crumb structure for plant growth is not known with certainty. It must allow the retention of the maximum amount of water available for the plant, but any excess must be able to drain away freely. There must also be free exchange of gases between the soil air and the atmosphere, otherwise the carbon dioxide content of the soil air may rise too high for healthy plant growth. Within the crumb the water-holding capacity is, as a rule, good but the air supply is poor; while between the crumbs the water-holding capacity is poor but the air exchange and drainage are both comparatively good. A. G. Doyarenko[2] working with podzolised soils at Moscow, and Kvasnikov[3] using a semi-arid soil type at Samara, found that the optimum crumb size was between 0·5 and 3 mm. Smaller crumbs merely blocked the coarser pores and restricted drainage and air supply without appreciably increasing the water-holding capacity, while larger crumbs had too poor an air supply within them and too much space between them, thus allowing plant roots to die from lack of water. With crumbs of optimum size, Kvasnikov showed that cereals made better growth, beginning earlier, giving

[1] See pp. 191, 226.

[2] *Russian J. Agric. Sci.*, 1924, **1**, 451. For a German summary of Doyarenko's and much other Russian work on soil structure see M. Krause, *Landw. Jahrb.*, 1931, **73**, 603.

[3] *Russian J. Agric. Sci.*, 1928, **5**, 459.

higher yields and higher values of the grain/straw ratio, with less consumption of water per unit of dry matter formed, than when the crumbs were either larger or smaller. The saving of water is probably associated with the fact that the osmotic pressure of the soil solution increases as the capillary pore space decreases, till it reaches a maximum in the 0·5 to 3 mm. crumbs.

A good soil structure should be stable against the pulverising effect of wind when dry and the shattering action of rain in a storm. It should also be water-stable (p. 192). Few structures occurring under arable conditions are sufficiently strong to resist both the shattering and the dispersing effects of torrential rain. In extreme cases this leads to severe losses of surface soil by erosion: quite frequently it causes a surface capping in which all the larger pores in the surface soil are blocked by dispersed clay and silt, forming, when dry, a hard surface that the young plant seedlings cannot break through, and that interferes with both the air and water supply to the plant.

A good soil structure should also resist the shattering effect of cultivation implements. The crumb structure can easily be ruined on many soils by using implements at the wrong time. If a heavy soil is ploughed when too wet, the mouldboard of the plough compresses the individual soil particles into a paste which dries to large hard clods. If a light soil is cultivated when too dry, many of the larger aggregates are broken down into dust, and thus become liable to wind erosion. One of the arts of cultivation is to choose the time and the implement so that a minimum amount of damage is done to the soil structure by the cultivation.

The Production of Soil Aggregates.

By Soil Cultivation.—One of the main functions of soil cultivation is to alter the size distribution of the aggregates

that occur in the field. The change may be in either direction: larger aggregates may be built up from smaller ones, or large aggregates may be broken down to smaller ones.

The building up of larger aggregates depends on the moisture content at which the soil is worked, and the amount of compression the soil suffers during working. Well-formed aggregates arise only within a fairly narrow moisture range and at the optimum moisture content they attain their maximum in number, in mechanical strength and in water stability,[1] the latter effect being most pronounced for aggregates over 5 mm. in size. The effect of amount of working depends on the water content: S. Henin [2] showed that on the dry side of the optimum moisture content, which in his case was near the sticky point of the soil, the strongest aggregation was given by the greatest working, but on the wet side by a moderate working.

The building up of soil structure by cultivation necessitates working the soil with an implement such as a mouldboard plough that compresses it at a time when it is suitably moist. But the method fails if the soil cannot be brought to the proper range of moisture contents. This may happen in arid and semi-arid regions if the soil never becomes sufficiently wet, or in humid regions where a heavy clay soil may never become sufficiently dry. In the latter case the land is simply laid down to grass.

The breaking down of large aggregates into smaller ones is easy for light soils: the lumps when dry are mechanically shattered. For heavy soils the problem is a little more difficult, but two agencies are successful where they are possible: wetting after drying: and frost. Clods must first be allowed to dry and then slightly moistened by rain: they can then be shattered comparatively easily. The reason is clear from Fig. 57; as the clod dries it contracts, but on re-wetting it

[1] D. Vilensky, *Trans. 1st Comm. Int. Soc. Soil Sci.*, Versailles, 1934, 97.

[2] *Ann. Agron.*, 1936, n.s. **6**, 455.

swells more than it contracted [1] because air has been entrapped in the finer capillaries; possibly also air absorbed by the dry colloidal material inside the crumbs is displaced by water and entrapped inside the clod.

A second method of breaking down large aggregates into smaller ones is to freeze the aggregates when moist. For heavy soils the effect is wholly beneficial. On freezing a wet lump of clay, the clay appears to contract round definite

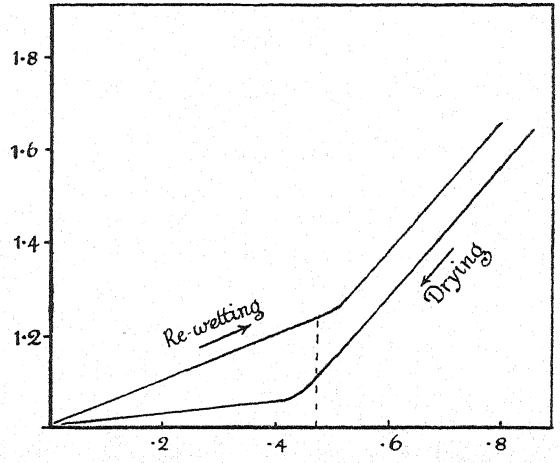


FIG. 57.—The volume of a given weight of moist soil depends not only on its water content but on whether it is drying down or being re-wetted (W. B. Haines, *J. Agric. Sci.*, 1923, **13**, 296).

centres, and to be compressed by the water that separates out and, on freezing, expands. Clay units are thus formed, separated by thin ice filaments, and as these thaw the units remain as crumbs if they are water stable. They cannot absorb as much water as could the original clod in bad structure; some of the water set free during the freezing can therefore drain away. The faster the rate of freezing the smaller is the size

[1] The expansion on wetting is confined to humus and clay soils: it does not take place in laterites where the colloids are mainly alumina and ferric oxide-hydrogels (F. Hardy, *J. Agric. Sci.*, 1923, **13**, 340).

of the crumbs formed; if the freezing is very rapid, as for example in liquid air, the crumbs are microscopic.[1]

The aggregates produced by freezing a heavy soil differ in shape from those produced by mechanically breaking a clod. On the heavy soil at Rothamsted after a frost nearly all the aggregates are between 30 mm. and 3 mm. in size: those formed mechanically have a much larger range of size. The aggregates formed by frost have also a more definite shape with flatter faces and sharper angles than those mechanically produced.

For light soils the shattering effect of the expanding ice filaments may be harmful, even when every effort is made to preserve a good lumpy structure, and many of the apparent contradictions in the literature on the effect of freezing on the formation of tilth are due to the fundamental differences between the aggregation of light and of heavy soils.

The arts of cultivation and of implement design consist in producing these compressions and shatterings at the appropriate moisture condition of the soil. A high degree of success has been empirically attained, and for the present science lags a long way behind practice.

By Modifying the Composition of the Soil.—Farmers and gardeners have long known that clay and organic matter, whether applied as dung or plant residues, had a potent effect in binding the particles of a sandy soil into good crumbs, while farmyard manure, and still more laying the land down to grass for a time, brought a heavy soil into a good crumb structure so that it could be ploughed and used as arable land as long as sufficient of the organic matter remained in the soil.

Further, it has long been known that dressings of chalk improve the texture of heavy clay soil.

These well-known facts are being investigated in soil laboratories. The binding effect on light soils is obviously attributable to the colloidal material added in the clay or the

[1] E. Jung, *Kolloidchem. Beih.*, 1931, **32**, 320; *Ztschr. Pflanz. Düng.*, 1931, A, **19**, 326.

organic matter. The effect on the heavy soils is more complex. Here the need is to increase the proportion of medium-sized, water-stable crumbs, and the organic matter does this, though it is not at present clear how.

The structure of the soil can be controlled in some degree by suitable cultivation, though for some soils and in some climates the amount of control available is insufficient for the production of a good tilth. In wet conditions heavy clays cannot be cultivated. In arid and semi-arid regions cultivation slowly destroys the stable structure of the virgin soil.[1]

F. J. Heltzer [2] in Turkestan and J. J. Kanivitza [3] in the Ukraine, both claim that growing a green crop and ploughing it in is much more efficient than adding dung. They attribute the effect to cellulose or hemicelluloses, in which plant residues are rich, but dung is poor. When they added cellulose to the dung before applying it, they much increased its efficiency.

The effect of growing leguminous crops such as clover or lucerne [4] and of putting the land down to perennial grasses [5] for two or three years has also been studied: both methods increase the organic carbon in the soil and probably build up structure more efficiently than dressings of farmyard manure. In particular, perennial grasses are claimed to give very stable and desirable structure, as they have done in the virgin chernozem and prairie soils.

These methods are probably applicable for all soils whether

[1] A. T. Tiulin, *Perm Agric. Expt. Sta., Dept. Agric. Chem.*, 1928, **2**, 77. A. H. Paschal, R. T. A. Burke and L. D. Baver, *Amer. Soil Survey Assoc. Bull.* No. 16, 1935, 44.

[2] *Trans. 1st Comm. Int. Soc. Soil Sci.*, Soviet Section, 1934, A, **2**, 73.

[3] Quoted by N. A. Sokolovsky, *ibid.*, Versailles, 1934, 89.

[4] A. T. Tiulin, *Chem. of Soct. Agric.*, 1933, 113; G. I. Pavlov, *2nd Int. Cong. Soil Sci.*, Moscow, 1932, **1**, 179; M. G. Chishevsky and Z. I. Kolobova, *Pedology*, 1935, Pt. 1, 7,

[5] G. I. Pavlov, *loc. cit.*; O. S. Rostovzeva and M. I. Avaeva, *Pedology*, 1935, Pts. 5 and 6, 797.

light or heavy because they increase the size of the water stable aggregates in soil.

Another method, possibly applicable only on acid, medium, or heavy soils, is to add lime. Tiulin [1] found that lime improved the structure in the second and later years after application, but Baver [2] was unable to find any correlation between the lime status and aggregation of prairie soil, and Henin [3] found that lime was harmful on the almost neutral fine sandy loam at Versailles.

Drawbar Pull and Plant Growth.—Definite relationships have been traced between drawbar pull (*i.e.* the pull that must be exerted to cause the plough to move through the soil), and plant growth, especially in its early stages. Eden and Maskell [4] found at Rothamsted a large negative correlation between the drawbar pull and the number of wheat plants surviving the winter ($r = -0{\cdot}8$) (Fig. 58), and also the number of tillers in early spring. Later in the season, however, a change set in, and the final yield showed practically no correlation with the drawbar pull. On the sparsely populated areas the extra moisture held by the clay and the freedom of competition from weeds and other wheat plants enabled the survivors to make greater growth than on the more densely populated areas so that their lack of number was partially counterbalanced by their greater size.

Plant Nutrients: Sources of Supply.

In a classical investigation Daubeny (1845) showed that only part of the total supply of plant nutrient elements in the soil was "active," or as we now say, "available"; the rest was "dormant." There is, however, no sharp line between available and unavailable plant foods in the soil. Some compounds, *e.g.* calcium nitrate, are available to all plants: others,

[1] *Perm. Agric. Expt. Sta., Dept. Agric. Chem.*, 1928, **2**, 77.
[2] *Amer. Soil Survey Assn. Bull.*, 1935, **16**, 55; 1936, **17**, 28.
[3] *Ann. Agron.*, 1936, n.s., **6**, 455.
[4] *J. Agric. Sci.*, 1928, **18**, 163.

e.g. some of the phosphates, are available to some plants but not to others. Lawes and Gilbert showed that plants growing side by side in a meadow took up not only different total amounts, but also different proportions, of the various nutrients.[1]

The older investigators attributed the different "feeding powers" to differences in the total acidity of the root sap; leguminous plants having, as they thought, higher root acidity than gramineous [2] had better powers of extracting insoluble

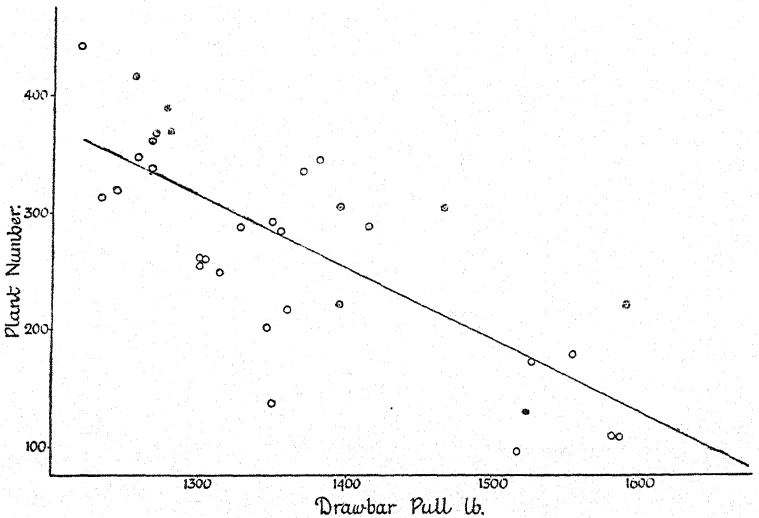


FIG. 58.—Relation between drawbar pull and numbers per row (22 yards) of wheat plants surviving the winter.

substances. This view was developed by Dyer (1894, 1901) and by Lemmermann (1907). Later investigators, finding no acid other than CO_2, showed that this could account for all the phenomena: this view was introduced by Czapek [3] and supported by Stoklasa; [4] it is now widely held though it does not

[1] *Phil. Trans.*, 1900, B, **192**, 139.

[2] But see p. 121.

[3] *Jahrb. wiss. Bot.*, 1896, **29**, 321.

[4] *Ibid.*, 1908, **46**, 55 (Stoklasa and Ernest). Their estimate of the amount of CO_2 evolved from barley roots (70 mg. per gram of dry matter in twenty-four hours) is now recognised as too high: 5 to 10 mg. per gram is a more usual result.

easily explain the great power of lupins to obtain phosphorus from compounds unavailable to other plants, which has been much studied by Prianischnikov in Russia [1] and by von Wrangell and others in Germany. Some dissolving action takes place outside the root hairs, for the soil phosphate becomes more soluble in the neighbourhood of the roots than away from them, as is shown by the fact that oats can obtain more phosphorus if grown along with lupins than if growing by themselves.[2] Differences in habit of root growth may also influence the uptake of nutrients from the soil.[3]

Even for the same plant, availability is not fixed but varies according to the oxygen supply to the roots, the temperature, and other conditions.

Nitrogen.—The older workers supposed that plants assimilated all their nitrogen as nitrate, but it is now recognised that ammonia may also be used, particularly on acid, grassland, and forest soils where nitrification may be slow and difficult.[4]

Neither ammonia nor nitrate normally occur in the soil in any great quantity : a usual range on land carrying vegetation is from 2 to 25 parts of nitric nitrogen, and about 2 to 10 parts of ammonia per million of soil, corresponding to about 1 to 3 per cent. of the total nitrogen, but cultivated fallows may contain two or three times this quantity by the early autumn, when the nitrate is at a maximum (p. 240).

[1] D. N. Prianischnikov, *Phosphorsäure*, 1934, **4**, 1 ; V. V. Butkevitsch, *Ztschr. Pflanz. Düng.*, 1933, A, **31**, 67 ; M. von Wrangell, *Phosphorsäureaufnahme und Bodenreaction*, Berlin, Paul Parey, 1920 ; see also *Landw. Vers.-Sta.*, 1920, **96**, 1, and *Landw. Jahrb.*, 1926, **63**, 627.

[2] Domontovitch, Shestakov, and Polossin, *Abh. Sowiet Sekt., Int. Bodenk. Ges.*, Komm. IV, 1933, **2**, 214.

[3] For a discussion of this subject see W. Thomas, *Plant Physiol.*, 1930, **5**, 443.

[4] Fr. Weis, *Zbl. Bakt.*, Abt. II, 1910, **28**, 434 ; H. Hesselman, *Medd. Skogförsöks.*, 1917, **14**, 923 ; also T. Gaarder and Oscar Hagem, *Medd. Forst. Førsøks. Sta. Vest. Norge*, Bergen, Nos. 4 and 11, 1921 and 1928. See J. Sebelien, *Bied. Zbl.*, 1931, A ; *Neue Folge*, **1**, 241 ; this article is a summary of Norwegian work on soil.

The whole of the nitrate present in the soil at any given time occurs in the soil solution : it may be washed out in the drainage water or assimilated by micro-organisms especially if carbohydrate energy material is present, or taken up by plants which during the first ten weeks of a vigorous growth absorb nitrate and may almost exhaust the supply.[1] Fresh supplies are produced by the action of micro-organisms on the reserve of nitrogenous organic matter, but the reaction is such that nitrates do not usually accumulate during plant growth.

Plants utilise nitrogenous nutrients much more efficiently when assimilated early in life than later on ; the best results are attained when nitrates can accumulate rapidly in spring when active growth begins. This depends on the general conditions in the soil rather than on the amount of reserve material : no sharp relationship exists between fertility and total percentage of nitrogen or of organic matter.

Potassium.—The exchangeable potassium in the clay and humus complexes and the easily decomposable potassium minerals apparently constitute the chief source of the plant nutrient. This idea of exchangeable or absorbed bases acting as nutrients was introduced by Liebig (1863) who, however, expressed it in different form : [2] the modern expression was given by Knop (1871) in a remarkable investigation of considerable historic interest. He supposed that the soil absorbed bases by some physical process, that these combined with silica or aluminium silicate to form some complex body, but that they could easily be displaced and therefore were readily taken up by plants. Soils of high fertility contained large

[1] For measurements with barley see G. R. Stewart, *J. Agric. Res.*, 1918, **12**, 311 ; J. S. Burd, *ibid.*, 1919, **18**, 51, and H. L. Richardson and E. M. Crowther, *J. Agric. Sci.*, 1935, **25**, 132.

[2] " The power of the soil to nourish cultivated plants," Liebig wrote, " is, therefore, in exact proportion to the quantity of nutritive substances which it contains in a state of physical saturation. The quantity of other elements in a state of chemical combination distributed through the ground is also highly important, as serving to restore the state of saturation, when the nutritive substances in physical combination have been withdrawn from the soil by a series of crops reaped from it."

quantities of easily displaced bases; he measured the amount by determining the ammonia absorbed from a 0·5 per cent. solution of ammonium chloride, assuming that, as absorption was only a substitution, the greater the amount of replaceable base the greater would be the absorption of ammonia. The method was applied to a number of soils and gave results in fair agreement with their agricultural history. It was somewhat modified by Kellner [1] who measured the quantities of potassium and calcium displaced and found they agreed with the amounts taken up by plants in pot culture.

Ramann (1905) accepted this view and it became widely adopted.[2] Later work, however, shows that plants can obtain from the soil more potassium than is held as exchangeable base. Horner [3] found that pineapples during the two years of growth took up 1670 lb. K_2O per acre from a soil which contained only 1036 lb. replaceable K_2O per acre foot. The available but non-replaceable potash was not readily estimated, however: the Neubauer method usually gave the best results.

Salminen considers that in Finland plants derive their potassium from mica, their calcium from plagioclase felspars and their phosphorus from apatite.[4]

Soils also vary in their behaviour to added potassium salts; some soils retain the potassium in such a way that practically all of it is ultimately recoverable by crops. Others hold it so firmly that only a small part is recoverable even after a number of crops have been taken in succession. (Fig. 59).

[1] O. Kellner, *Landw. Vers.-Sta.*, 1886, **33**, 349.

[2] For a study of Scottish soils showing the close relationship between available and exchangeable potash see R. Stewart, *J. Agric. Sci.*, 1929, **19**, 524.

[3] J. M. Horner, *Hawaii Pineapple Canners' Sta. Bull.* No. 13, 1930. See also F. A. E. Abel and O. C. Magistad, *J. Amer. Soc. Agron.*, 1935, **27**, 437, and D. R. Hoagland and J. C. Martin, *Soil Sci.*, 1933, **36**, 1; *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 99.

[4] A. Salminen, *J. Sci. Agric. Soc.*, Finland, 1931, **3**, 153.

Unlike the nitrate the whole stock of nutrient potassium is not present in the soil solution but only part, and the relationship between the concentration of potassium in the

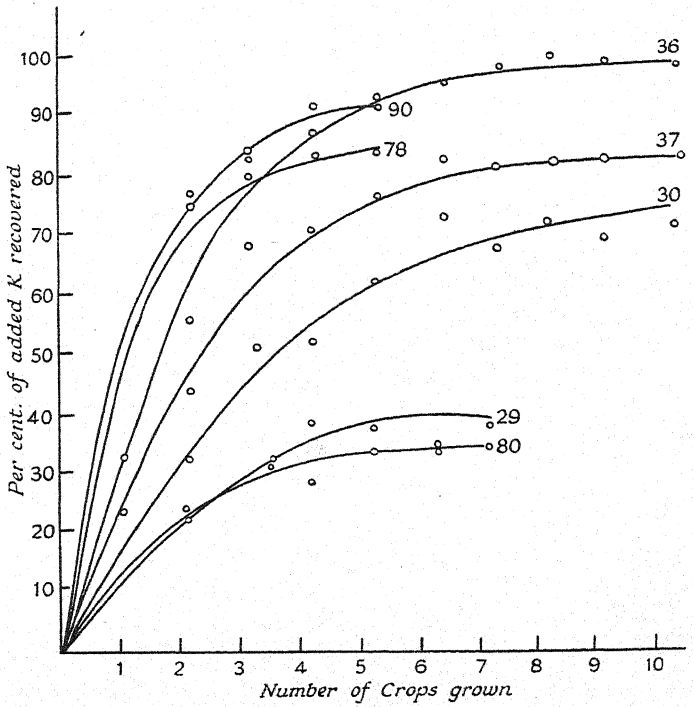


FIG. 59.—Recovery of added potassium by a succession of barley and tomato crops grown in different soils (Hoagland and Martin). *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 99.

For soils 30, 36 and 37, crops 1, 2, 4, 7 and 9 were barley, while crops 3, 5, 6, 8 and 10 were tomato; for soils 29, 78, 80 and 90, crops 1, 3, 5 and 7 were barley, while crops 2, 4 and 6 were tomato. (Recovery calculated on basis of comparison between NP and NPK fertilised soils.)

solution and the amount of moisture in the soil accords with the idea of an absorption equilibrium.

Calcium.—Three sources of calcium appear to be available to the plant: the nitrate, some of the minerals, especially the carbonate, and the exchangeable calcium. As the nitrate

increases in the soil solution through bacterial action so the calcium increases ; calcium bicarbonate is also present in the solution.

In regard to the growing plant calcium presents the special feature that some tolerate a good deal and others tolerate but little of it in the soil (p. 593).

Phosphorus.—Three groups of phosphorus compounds occur in the soil [1] :—

(*a*) Inorganic phosphorus in neutral soils : probably a calcium phosphate : hydroxyapatite.

(*b*) Inorganic phosphorus in acid soils : presumably combinations with iron and aluminium.

(*c*) Organic phosphorus compounds, presumably of value only after they have been decomposed by micro-organisms and their phosphorus converted into inorganic phosphates.

The amounts of phosphate in the soil solution are very small owing to the presence of calcium and magnesium : and even allowing for the fact that plants can assimilate phosphate from exceedingly dilute solutions,[2] they are wholly inadequate for plant nutrition without frequent renewal.[3] As the concentration does not vary with the moisture content it is supposed that the soil solution is always saturated.

The rate of renewal of phosphorus in the soil solution, or the rate at which the phosphorus becomes available to the plant, depends partly on the soil and partly on the plant. M. von Wrangell [4] shows that renewal takes place most rapidly in sandy soils of low absorptive power, and much more slowly in clay and humus soils of high absorptive power.

[1] P. 240.

[2] From solution as weak as 0·1 part P_2O_5 per million, according to von Wrangell. F. W. Parker has investigated the insufficiency of the phosphate in the soil solution (*Soil Sci.*, 1927, **24**, 129).

[3] Some workers, *e.g.* A. W. Greenhill, have argued that the plant must absorb solid phosphate (*J. Agric. Sci.*, 1930, **20**, 559). N. M. Comber has suggested a mechanism by which this might be possible (*J. Agric. Sci.*, 1922, **12**, 363).

[4] *Landw. Jahrb.*, 1926, **63**, 627 and 677.

Chemists have generally assumed that only the more soluble phosphorus compounds are likely to serve as nutrients, and they have therefore devised methods for dividing up the phosphates into a more and a less soluble fraction. Generally they have used dilute acids, and of these Dyer's 1 per cent. citric acid (1894, 1901) has been most widely used in Great Britain, in the United States by the Pennsylvania State College workers, and in Germany by Lemmermann and Fresenius.[1] No two acids give the same results,[2] and even the same acid gives different results if the conditions are altered. Russell and Prescott[3] found that two reactions proceed simultaneously: the acid rapidly dissolves the P_2O_5; but the P_2O_5 then reacts with some of the soil constituents and is again precipitated. The dissolving action was the same for dilute hydrochloric, nitric, and citric acid, of equivalent strengths; the reverse action was different, hence the net amount of P_2O_5 determined by the analyst differed for all these acids.

In consequence of the difficulty of interpreting the chemical analyses biological methods have been devised for estimating the amount of available phosphate in the soil. The bacteriological methods have already been mentioned (p. 476): a method of analysis by the plant itself has been devised by Neubauer and is used with much success.[4] A modification has been developed by H. Wiessmann.[5] Mitscherlich has devised a method of pot culture experiments which gives information about the need or otherwise of supplying phosphatic and potassic fertilizers and the amounts most likely to be effective: this has proved helpful for advisory work.[6]

[1] *Ztschr. Pflanz. Düng.*, 1927, B, **6**, 163.

[2] See Hall and Plymen (1902) and Hall and Amos (1906) for a comparison of a number of soils.

[3] *J. Agric. Sci.*, 1916, **8**, 65.

[4] For a description see H. Neubauer and W. Schneider, *Ztschr. Pflanz. Düng.*, 1923, A, **2**, 329.

[5] *Landw. Vers.-Sta.*, 1928, **107**, 275. For a full account of these methods see R. Stewart, *Imp. Bur. Soil Sci.*, Rothamsted, Tech. Comm. No. 25, 1932.

[6] E. A. Mitscherlich, *Die Bestimmung des Düngerbedürfnisses des Bodens*, Berlin, Paul Parey, 1925.

There are some soils from which plants have considerable difficulty in obtaining the phosphorus they need. Among them are soils containing much iron oxide, such as the red soils of hot countries and some soils of temperate regions; the iron oxide easily combines with phosphoric acid and fixes it so firmly that plants cannot extract it. Phosphatic manures such as superphosphate have but little effect because the phosphate is held by the soil and so cannot easily be taken up by the plant. So far no simple and effective method has been devised for overcoming the difficulty.

The reaction of the medium is the chief factor determining the availability of the phosphate in sands containing much iron and aluminium, and in consequence the physiological reaction (p. 130) of the nitrogen compounds supplied plays an important part.[1]

Another case is that of calcareous soils. Breazeale and McGeorge,[2] in Arizona, show that phosphate is fixed in presence of calcium carbonate to form a very insoluble substance unlikely to be of any use to plants. This may easily happen if the soil reaction is slightly alkaline (*p*H above 7·6).

Plants also vary in the ease with which they can extract phosphorus from the soil. Lupins are better able to do this than most other crops; having assimilated the phosphorus they store it in their leaves and other organs and when the crop is ploughed into the soil the phosphate becomes more available for the next crop than it otherwise would have been (p. 403).

The crops that can obtain phosphorus least readily from the soil are not necessarily those which are most sensitive to phosphorus starvation nor which respond best to additions of phosphatic fertilisers: the order is approximately as follows:—[3]

[1] P. Strebeyko, *Rocz. Nauk Roln.*, Poznań, 1935, **34**, 202.

[2] J. F. Breazeale and W. T. McGeorge, *Ariz. Agric. Expt. Sta. Tech. Bull.* No. 41, 1932.

[3] E. J. Russell, "Artificial Fertilizers," *Min. Agric. Bull.* No. 28, 2nd ed., 1932, pp. 88 *et seq.*

Ability to obtain Phosphorus from Relatively Insoluble Phosphates.	Responsiveness to further Additions of Phosphate.	Sensitiveness to Phosphate-Starvation.
Most.—Lupins, lucerne.	Potatoes.	Swedes and turnips.
Swedes, cabbage, and turnips.	Swedes and turnips.	Potatoes.
	Mangolds.	
	Barley.	Oats.
	Hay.	
Least.—Oats, wheat, barley, and potatoes.	Oats and wheat.	Hay.

The property of obtaining phosphorus from insoluble phosphate is not entirely determined by the power of rapidly taking up calcium, because clover can do this and yet it is much inferior to lupins in its power to utilise insoluble phosphates.

Reference to page 63 shows that the plants recorded there as utilising ammonia most readily have most difficulty in obtaining phosphorus from its less soluble compounds, while lupins, which have the greatest power of utilising insoluble phosphates, have least power of utilising ammonia.

Organic Matter.—While plants can grow satisfactorily and attain full development with inorganic nutrients only, yet, in natural conditions, their nutrition always proceeds in presence of organic matter. There has been much discussion as to whether this plays any active part in the process.

The experimental evidence is not very definite.

In the Rothamsted field experiments with cereals, no combination of artificial fertilisers is as effective as farmyard manure [1] in avoiding deterioration of yield on continuously cropped land, or in steadying crop yields from year to year, but the effects could be attributed to differences in nutrient supply or to physical and physico-chemical actions of the manure on the soil (p. 209).

A stricter comparison with artificial fertilisers was made in the Askov experiments, which continued for 20 years, and in which the quantities of nutrients were made the same for

[1] The amounts of nutrients supplied, however, are not the same.

both. Here the artificial manures proved distinctly superior to farmyard manure: indeed it required twice as much nutrient in the form of farmyard manure to give the same effect as a given dressing of artificial manure.[1]

There are, however, a number of cases where farmyard manure seems to have some special effect not producible by artificial manures.

Potatoes, sugar beet and various other root crops, also certain fruit bushes respond particularly well to farmyard manure. The improvement in physical condition of the soil resulting from the use of farmyard manure may afford a sufficient explanation in these cases.

Leguminous crops are specially benefited by straw or undecomposed farmyard manure. Here the facts are explicable on the ground that the straw locally stimulates nitrate assimilation by the soil organisms and this in turn stimulates the nitrogen-fixing process (pp. 398, 409).

There still remain observations, however, that cannot be thus explained and that suggest some special stimulating effect of certain organic substances under certain conditions. Subrahamanyan and his colleagues[2] increased the growth of sunflowers by injecting into the plant or applying to the soil minute amounts of yeast, dried blood, manure and sewage effluent extracts. It has long been known that small quantities of humus, or extract of farmyard manure or of certain organic substances, some of which occur in the soil, have a special stimulating effect on plants grown in water culture. *Lemna* is a favourable plant for demonstration, though Niklewski has used crop plants.[3] The effect of the trace of

[1] K. Iversen, *Ztschr. Pflanz. Düng.*, 1928, B, **7**, 457. Reviews of the older work by O. Lemmerman, *Ztschr. Pflanz. Düng.*, 1932, B, **11**, 1; M. Gerlach, *ibid.*, p. 385; A. W. Blair, *J. Amer. Soc. Agron.*, 1933, **25**, 540, lead to a general conclusion that after allowing for ordinary nutritive and physical effects there is little left to account for.

[2] *Proc. Indian Acad. Sci.*, 1935, **1**, 607; **2**B, 201.

[3] W. B. Bottomley, *Proc. Roy. Soc.*, 1915, B, **88**, 237, and other papers in the same *Proc.* to 1920, **91**, 83; F. A. Mockeridge, *Biochem. J.*, 1920, **14**, 432; E. Ashby, *Ann. Bot.*, 1929, **43**, 805; B. Niklewski, *Doświadcz*

humus is attributed by Olsen to its facilitating the assimilation of iron. Niklewski shows that other colloidal materials behave in the same way so long as the solution does not become too acid (*e.g.* if the *p*H remains about 6 or 7). As the quantity given is too small to have any nutritive effect he suggests that the colloid may increase the permeability of the cell wall.

Stimulating effects of this kind, however, are only rarely recorded for plants growing in soil. The only reliable instance known to the writer is that given by Hartley and Greenwood in Nigeria [1] where small applications of farmyard manure at the rate of only 1 ton per acre had notable effects, considerably surpassing the equivalent mixture of artificial manures. At Woburn, on the other hand, small dressings of about 4 tons per acre of farmyard manure had no important effects on the yields of wheat or barley though dressings of 8 tons per acre gave considerable increases in yield.

When soil is heated to 100° C., E. J. Russell and F. R. Petherbridge [2] showed that something is formed which stimulates root-development to a remarkable extent: possibly it is present in unheated soils also.

Certain bacterial excretions also stimulate the development of root hairs on lucerne plants (p. 394). Grandeau (1872) long ago maintained that humus played the chief part in the nitrogen nutrition of plants and in their phosphorus nutrition; for this there is no direct evidence, but it is known that farmyard manure produces striking results on phosphate-starved land.[3]

Roln., 1931, **7**, Part 3, 3, and *Jahrb. wiss. Bot.*, 1933, **78**, 431; C. Olsen, *C.R. Lab. Carlsberg*, 1930, **18**, 1. For various organic substances, isolated from the soil, see O. Schreiner and E. C. Shorey, *U.S.D.A. Bur. of Soils*, Bull. No. 74, 1910.

[1] K. T. Hartley and M. Greenwood, *Emp. J. Expt. Agric.*, 1933, **1**, 113.

[2] *J. Agric. Sci.*, 1912, **5**, 86, and *J. Bd. Agric.*, 1912, **18**, 809; 1913, **19**, 809; 1914, **21**, 97.

[3] See G. Scott Robertson, *J. Min. Agric., Northern Ireland*, 1927, **1**, 7.

Plant Nutrients: The Soil Solution.

Whitney in 1892, and later on he and Cameron, put forward the view that the plant obtains its nutrients from the solution present in the soil. He built around this idea an elaborate hypothesis of soil fertility which evoked much controversy and much of which proved unacceptable, but his view that the soil solution is the culture solution of the plant has survived and is now generally adopted; it has been elaborated and brought into conformity with modern physical ideas by D. R. Hoagland, J. S. Burd, J. C. Martin, and their colleagues at the California University.[1]

The Composition of the Soil Solution.—As has often happened in the history of agricultural science, the first investigation was made in France; Schloesing, in 1866, devised a method of collecting the soil solution based on displacement by water. He placed 30 to 35 kgrm. of freshly taken soil in a large inverted tubulated bell jar and poured on it water, coloured with carmine, in such a way as to simulate the action of rain. The added water at once displaced the soil water and caused it to descend so that it could be collected: a sharp horizontal line of demarcation between the added and the original water persisted throughout the experiment even when eight days were occupied in the descent. A typical analysis of the displaced liquid in milligrams per litre was:—

SiO_2.	Nitric Acid.	Carbonic Acid.	CaO.	MgO.	K_2O.	Na_2O.	Sulphuric Acid.	Chlorine.	Organic Matter.
29·1	305	118	264	13·5	6·9	7·8	57·9	7·4	37·5

and in addition traces of phosphorus and of ammonia. This soil contained 19·1 per cent. of water.

The total concentration is seen to be about 0·08 per cent.

Burd and Martin adopted the following method:—[2]

[1] See Burd and Martin (*Hilgardia*, 1931, **5**, 455) for a summary of their work.

[2] *J. Agric. Sci.*, 1923, **13**, 265.

They forced water under pressure (100 lb. per sq. inch) through the fresh, moist soil (2 kilos) contained in narrow brass cylinders, and collected the percolating liquid in 10 c.c. fractions. The first lots are uniform in composition as shown by their electrical conductivity, and are assumed to represent the true soil solution.

Doyarenko [1] extracted the solution by rubbing the fresh sample of soil with pure heavy paraffin oil (vaseline oil) so as to make an emulsion which was then pressed out and centrifuged.

Whitney supposed that the soil solution was approximately constant in composition, being a saturated solution of the minerals common to all soils. This proved to be incorrect; [2] the concentration and composition of the soil solution vary continuously, being modified by at least three factors: the amount of soil moisture, the action of the plant, and the action of the soil organisms.

Relation to Soil Moisture.—(*a*) The concentration of nitrate, chlorine, and calcium varies inversely as the moisture content, indicating that the whole of the chlorine and the nitrate in the soil is in the soil solution along with an equivalent amount of calcium, and in heavy soils some magnesium.

(*b*) The concentration of phosphate, though varying from soil to soil, is independent of the moisture content; the soil solution being presumably saturated with phosphate and dissolving more or throwing some out according as it is greater or less in amount; usually about 1 to 3 parts per million are present.

(*c*) The concentration of potassium increases as the soil solution becomes more concentrated, but not proportionally. This suggests that the available potassium is not all dissolved in the soil solution at the outset, but that it is partly in the solution and partly absorbed by the soil: the solution and the soil are in some kind of equilibrium.

[1] *Versuchsfeld f. Allgem. Ackerbau, Landw. Akad.*, Moscow, 1924-1927, No. 2, p. 1.

[2] A. D. Hall, W. E. Brenchley, and L. M. Underwood, *Phil. Trans.*, 1913, B, 204, 179.

Table 93 gives typical figures showing the composition of the solution in Burd and Martin's experiments. Figures of

TABLE 93.—COMPOSITION OF SOIL SOLUTION. BURD AND MARTIN, CALIFORNIA (*Soil Sci.*, 1924, **18**, 151.)

Solutions displaced by water from cropped soils at beginning (April) and end (September) of growing season (1923) and at the beginning of the next growing season (1924).

Soil.	Date.	*p*H.	Parts per Million of Displaced Solution.								
			NO_3.	HCO_3.	SO_4.	PO_4.	Ca.	Mg.	Na.	K.	Total Solids.
No. 7: 12·5 per cent. moisture	Apr. 30, 1923	7·4	149	83	561	1·1	242	91	42	21	1190
	Sept. 4, 1923	7·6	58	155	432	0·6	193	47	40	9	935
	Apr. 28, 1924	7·6	252	142	699	0·6	336	76	59	12	1527
No. 11: 12·4 per cent. moisture	Apr. 30, 1923	8·2	173	160	671	3·3	222	97	87	41	1454
	Sept. 4, 1923	7·6	16	234	598	1·2	192	64	44	22	1171
	Apr. 28, 1924	8·1	263	259	785	2·9	276	94	78	35	1793

TABLE 94.—CONCENTRATION AND COMPOSITION OF SOIL SOLUTION IN DIFFERENT CONDITIONS. PARTS PER MILLION. A. W. TROFIMOV, MOSCOW.[1]

Late Fallow.	Soil Moisture, per Cent.	Total Dry Matter.	Total Salts.	Osmotic Pressure, Atmos.	Nitrogen as NH_3.	Nitrogen as NO_3.	Soil Moisture, per Cent.	Total Dry Matter.	Total Salts.	Osmotic Pressure, Atmos.	Nitrogen as NH_3.	Nitrogen as NO_3.
April	19·8	1050	360	0·45	4·4	10·8	18·3	830	—	0·45	40·5	5·4
August	21·3	1470	390	0·50	14·5	50	20·4	1340	350	0·45	17	48
	Drier Conditions.						*Moister Conditions.*					
15 April	18·8	1450	340	0·50	43	15·5	20·5	1020	210	0·75	36	10·2
5 May	15·9	1360	420	0·50	—	18	18·9	3100	1500	1·40	37	84 160
7 June	17·0	2950	850	1·15	32	59	18·7	3700	1400	1·40	18	57(?) 20
21 July	22·0	1500	710	0·35	13	93	23·9	2550	800	—	—	174
26 July	18·9	1100	430	0·35	—	72	—	—	—	—	—	—
10 August	19·2	1560	640	0·80	15	89	21·7	2700	800	0·8	15	154

[1] *Versuchsfeld f. Allgem. Ackerbau, Landw. Akad.*, MOSCOW, 1924-1927, No. 2, p. 11.

much the same order were obtained by Trofimov working in Doyarenko's laboratory (Table 94).

Relation to Plant Growth.—The growing plant depletes the soil solution of much of its nutrient material, including almost the whole of the nitrate, but the solution is not absorbed as a whole; there is considerable selection. Fig. 60 and Table 93

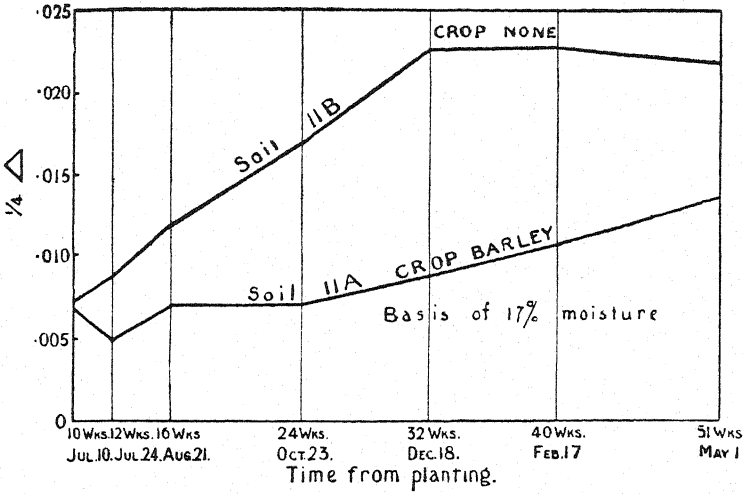


FIG. 60.—Variations in concentration of soil solution with crop and season, showing that the barley crop much lowers the concentration even after its removal in August. On the vertical axis one-quarter of each freezing-point depression is plotted: an approximate estimate of the corresponding osmotic pressure is obtained by multiplying the plotted value by 50 (D. R. Hoagland, *J. Agric. Res.*, 1918, **12**, 369; see also Bouyoucos and McCool, *Michigan Tech. Bull.* No. 24, 1916, and No. 31, 1917).

show some of the California results: the effect of the crop is seen to persist for a long time after it is removed.

Relation to Micro-organic Activity.—Micro-organisms restock the soil solution with the nutrients that the growing plant has taken. Their activity produces anions which bring an equivalent amount of cations into solution. Leached soils stored under sterile conditions (in contact with toluene) gained little or no soluble material in a year, while the same soils

without toluene, and therefore subject to micro-organic activity, gained considerably in soluble matter.[1] The anions produced are nitrate (chiefly), sulphate, and bicarbonate; the bases brought into solution are usually calcium and magnesium.

Trofimov's results (Table 94) illustrate the interaction of moisture, micro-organic activity, and composition of soil solution. Working in the field on plots under different fallow conditions he found that methods conserving soil moisture during summer raised the concentration of nitrate and of dry matter in the soil moisture and therefore the osmotic pressure.

Other investigators have obtained results of the same general kind. The total concentration of the soil solution in ordinary agricultural soils, and excluding saline soils, is usually about 0·05 to 0·02 per cent.: the osmotic pressure is about 0·2 to 1 atmosphere. The solution is thus very dilute, much more so than the root sap, the osmotic pressure of which is some 7 to 20 atmospheres. It is not at all clear how the ions pass from the soil into the root.[2]

The Soil Solution and Soil Fertility.

The soil solution contains the whole of the nitrate that is ready for the plant, much of the potassium, but only a fraction of the phosphate. It contains as we have seen some 50 to 300 parts per million of nitric nitrogen, 10 to 40 parts of potassium, but only about 1 or 2 parts of phosphate (PO_4). Broadly speaking, the more fertile soils have the higher concentration of soil solution, but there is no close connection between fertility and concentration, indeed in water-culture experiments dilute solutions may give as good growth as concentrated solutions, provided they are sufficiently rapidly renewed.

[1] Martin and Hoagland. See J. S. Burd, *Soil Sci.*, 1925, **20**, 269.

[2] For a discussion and bibliography see G. E. Briggs, *Proc. Roy. Soc.*, 1930, B, **107**, 248; W. Thomas, *Plant Physiol.*, 1930, **5**, 443; W. J. V. Osterhout, *Biol. Rev.*, 1931, **6**, 369; F. C. Steward, *Ann. Rev. Biochem.*, 1935, **4**, 519; D. R. Hoagland and T. C. Broyer, *Plant Physiol.*, 1936, **11**, 471, and P. Prevot and F. C. Steward, *ibid.*, 509.

The rate of renewal of the dissolved substances is one of the important properties of the soil-water system. For phosphorus it must be considerable, as already shown (p. 524); for potassium the question of renewal is usually less important as more of it is present in the soil solution; for nitrate the rate of renewal is dependent entirely on the activity of the micro-organisms.

Soils lying at the foot of a slope may receive much drainage water from higher ground, and this mass movement causes a constant renewal of the soil solution. Apart from these seepage effects there appears to be little diffusion of ions in the soil. A grass field at Rothamsted, originally uniform in its herbage, was in 1856 divided into plots each of which actually touches its neighbours: certain manurial treatments have been given annually to each and continued without change (on most plots) ever since. Marked differences in herbage have resulted, but the edges bounding the plots are fairly sharp; there is no evidence of much lateral diffusion in the period of seventy years.[1]

Soil Reaction: Soil "Sourness."

Farmers apply the term "sour" to soils which are improved by liming: it applies to two sets of conditions:—

(1) Acidity, as shown by lime requirement and *p*H measurements.

(2) Shortage of calcium, which causes poor physical conditions in the soil, and leads to serious nutritional disturbances in the plant.

These two conditions are so closely interwoven that it is not possible in field conditions to distinguish between them.

Most of the investigations have been made on acidity, and these alone will be dealt with here.

In their behaviour towards soil reaction plants can be divided into three groups:—

[1] For studies of diffusion of salts in soil see L. C. Wheeting, *Soil Sci.*, 1925, **19**, 287 and 459.

(1) Those tolerating only small variations in soil reaction, the optimum being at or about the neutral zone or on the alkaline side.

(2) Those tolerating only small variations in soil reaction, the optimum being on the acid side.

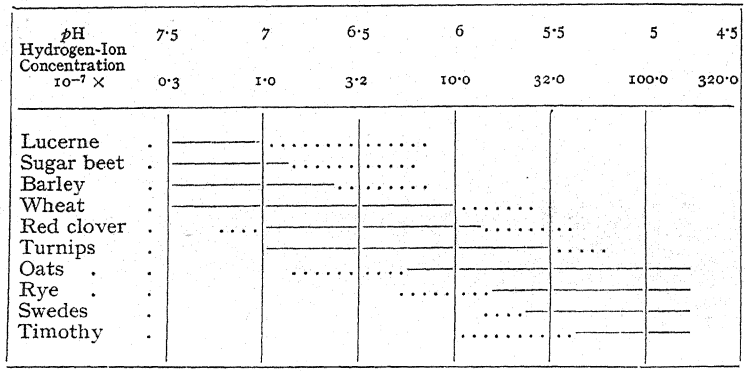
(3) Those tolerating considerable variation in soil reaction.

The simplest case is presented by agricultural crops, most of which fall into the first and third groups.

The range of acidity within which given crops are usually cultivated is shown in Table 95, giving Arrhenius' survey of some 200 Swedish farms.

TABLE 95.—SOIL REACTION AND PLANT GROWTH: SURVEY OF ABOUT 200 FARMS. ARRHENIUS (1926).

The unbroken lines indicate frequent occurrence and good yields: the dotted lines poor yields and less common occurrence.

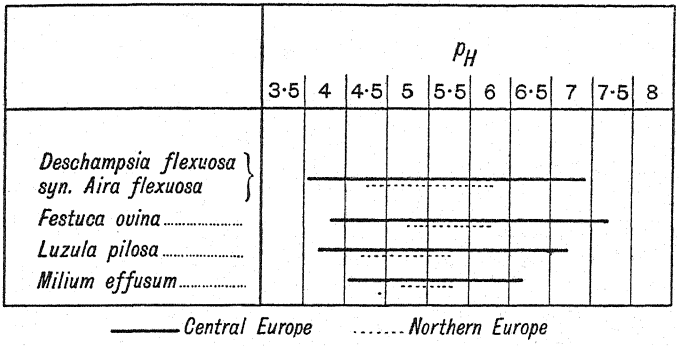


The order of tolerance is much the same wherever the crop is grown but the actual limits vary. Table 96 shows that the limits recorded for various grasses growing in Central Europe are wider than for the same grasses growing in Northern Europe. Hendrick's [1] determinations in Scotland show a general greater tolerance for acidity in Scotland than in Arrhenius' table.

[1] J. Hendrick and W. Moore, *Trans. Highland Agric. Soc.*, 1935, Ser. 5, **47**, 34; see also H. E. G. Emmett and E. Ashby, *Ann. Bot.*, 1934, **48**, 869.

Lucerne, sugar beet, barley, wheat, and clover belong to the group least tolerant of acidity : the others, excepting perhaps rye, belong to the more tolerant group : their absence from

TABLE 96.—LIMITS OF TOLERANCE OF ACIDITY BY CERTAIN GRASSES IN CENTRAL AND IN NORTHERN EUROPE. D. FEHÉR AND L. KISS (*Bot. Arch.* 1933, **36**, 53). LATITUDES 47° 47′ TO 69° 20′.



the neutral soils arises not from intolerance but from the fact that farmers having neutral soils prefer to grow the first five crops in the list. English and American experience is shown in Table 97. For advisory work lists such as this have great value. There is an obvious advantage of growing crops suited to existing soil conditions rather than attempting costly changes over a large area. Thus on certain sour soils in Yorkshire farmers tend to confine themselves to oats, potatoes, and rye, and do not attempt barley or red clover. Near Leeds where even the rain water is acid, rhubarb is extensively grown.[1] It is not possible, however, to draw up precise lists or to assign definite optimum *p*H values for any of the plants ; the value in any particular instance being affected by the amounts of calcium, organic matter, moisture, and by other factors.

The effect of acidity is masked by dressings of farmyard

[1] For a study of sugar beet and *p*H values see G. Newlands, *J. Agric. Sci.*, 1928, **18**, 704.

TABLE 97.—DEGREE OF TOLERANCE OF SINGLE CROPS TO SOURNESS OR ACIDITY.

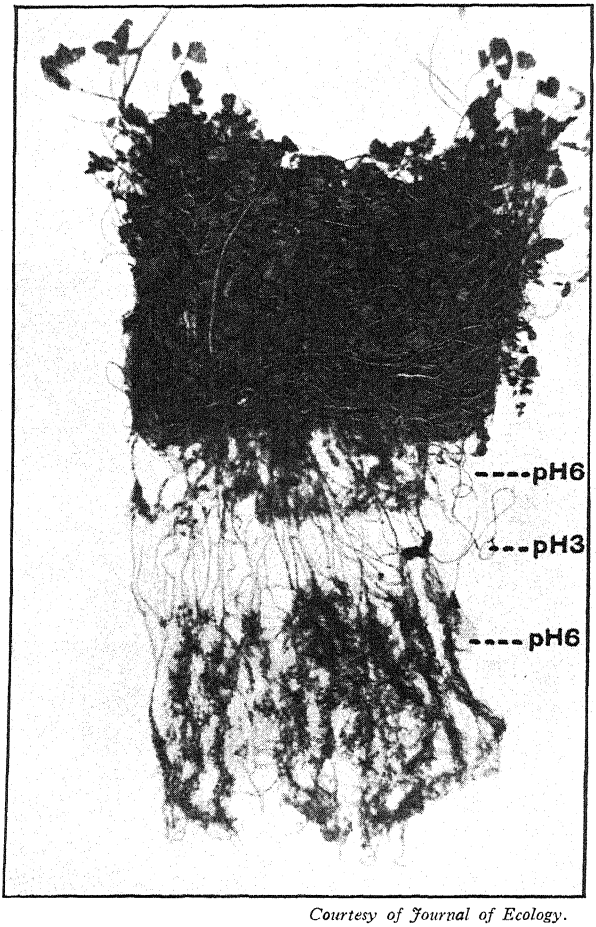
England.		Rhode Island.[1]	
Less Tolerant.	More Tolerant.	Less Tolerant.	More Tolerant.
Red clover	Cabbage and kale	Red clover	Beans
Foxtail (*Alopecurus pratensis*)	Cocksfoot	*Alopecurus prat.*	Maize
Barley	White clover	Lucerne	Potatoes
Peas, beans, and vetches	Swedes	*Poa pratensis*	Tomato
Wheat	Oats	*Dactylis glomerata*	*Agrostis canina*
Mangolds	Alsike	Barley	*Agrostis vulgaris* (most tolerant)
Sugar beet	Potatoes		
Mustard	Rye		
Rye grass	Lupins		
	Sweet vernal grass (*Anthoxanthum*)		
	Sheep's fescue		
	Yorkshire fog (*Holcus lanatus*)		
	Sorrel (*Rumex acetosa*)		
	Rhubarb (most tolerant)		

manure, and it is usually more pronounced in dry than in wet conditions.

In the south of England fertile conditions are associated with *p*H 7, but in the west in Wales, and in Scotland lower *p*H values, 6·5 or even 6, appear to be quite satisfactory.

Crops grown in soils that are too acid show certain characteristic appearances. The extreme case where the plant only just survives is well seen on the Woburn barley plots that have become acid (*p*H = 4·5). The roots are yellowish-brown and very stunted with short branches and abrupt ends; they lack the clean white rootlets of normal plants; they do not strike down into the soil but may curl round as if to avoid it. The seedlings develop; the leaves have a dull purplish appearance; they are stiff but the stem never elongates, and at harvest time the plants are only a few inches

[1] B. L. Hartwell and S. C. Damon, *R.I. Agric. Expt. Sta. Bull.* No. 160, 1914. For American experience see also F. V. Coville, *U.S.D.A. Bull.* No. 6, 1913; E. Truog, *Soil Sci.*, 1918, **5**, 169.



Courtesy of Journal of Ecology.

FIG. 61.

Root structure of *Trifolium repens* in relation to soil acidity.
(G. H. Bates, *J. Ecol.*, 1934, *22*, 271)

high, yet they have formed some grain and its nitrogen content is quite normal.[1] Mangolds in like manner develop but never grow large. Where successive layers of soil differ in their reaction the roots develop freely in the neutral layers but only scantily in those that are more acid (Fig. 61).

The marginal case where acidity is only just beyond the range of tolerance is very common in the field. The distribution of the acidity is often local, and this factor, taken in conjunction with the modifying effect of soil conditions, leads to considerable inequalities of growth. This characteristic appearance is of considerable help in diagnosing incipient acidity. No other factor causes so patchy an appearance in the field. Arable crops, especially clover and sugar beet, fail in places and elsewhere thrive vigorously, suggesting a stimulating effect of the marginal degree of acidity.[2] On grass land some species, notably *Festuca ovina* and *Anthoxanthum*, are dark green while others are yellowish.[3]

An important effect of the weakening of the crops on acid land is to allow the growth of weeds which tolerate the acidity, but would not tolerate the competition of a full crop. Thus farmers commonly regard mayweed (*Matricaria*) among the wheat on heavy land, spurry (*Spergula arvensis*) among the barley and roots on lighter land, sorrel and bent grass (*Agrostis*) on grassland as indications of sourness.

The phenomena are more complex in natural conditions where there is a mixed flora. The element of competition, one of the most important factors affecting plant growth, now comes in. Plants that can tolerate acidity somewhat better

[1] For a full description with chemical analyses see H. H. Mann, *J. Agric. Sci.*, 1936, **26.**

[2] The permanent wheat on the acid plots at Woburn affords a good example: see E. J. Russell and J. A. Voelcker, *Fifty Years of Field Experiments*, p. 226.

[3] The most striking colour change is that produced in the flowers of hydrangeas. Atkins (*Sci. Proc. R. Dublin Soc.*, 1923, **17**, 201) states that the flowers are blue when the soil *p*H is 6 or less; pink when it is 7·5 or more; and blue and pink on the same plant when the *p*H is between 6 and 7·5.

than their competitors survive while the others die; they dominate the flora of acid soils, not because acidity is necessarily their optimum condition, but because, like other adverse factors, it alters the balance in competition in favour of these plants that can tolerate it and against others which are eliminated.

A second factor frequently restricts the flora on acid land undisturbed by cultivation. Owing to the diminished activities of earthworms [1] and micro-organisms (pp. 467 *et seq.*) the dead vegetation lying on the surface of the soil is not decomposed during autumn and winter, but persists through spring and summer, forming a mat through which only few kinds of plants can penetrate, all others dying as seedlings.

A third factor is that certain disease organisms are very tolerant of acid conditions and may do much injury to the growing plant.

The operation of these factors is, as might be expected, much influenced by other conditions, so that it is not possible to arrange plants in absolute order of dominance in the floras of acid soils. But where the general conditions are in other respects similar certain floristic differences are commonly associated with different degrees of acidity. Ecologists have studied many of these communities.[2]

One of the most exhaustive investigations is that made by C. Olsen.[3] His field results were analysed statistically—the only satisfactory treatment of masses of field data. Some of his figures are given in Table 98.

Of other species the distribution is as follows :—

[1] Absence of worm-casts on grassland is a common sign of acidity (p. 453).

[2] For an interesting study of the Swiss ecological communities corresponding to different ranges of *p*H values see F. Chodat, *Bull. Soc. Bot. Genève*, 1924, **16**, 36. For English studies see E. J. Salisbury, *J. Ecol.*, 1916, **4**, 83; 1918, **6**, 14; W. E. Brenchley, *Ann. Bot.*, 1911, **25**, 155, and 1912, **26**, 95; T. Eden, *J. Ecol.*, 1924, **12**, 267.

[3] *C.R. Lab. Carlsberg*, 1923, **15**, 1.

*p*H 4·5 or less : [1] *Vaccinium myrtillus, Deschampsia flexuosa, Carex pilulifera, Luzula pilosa, Convallaria majalis, Maianthemum bifolium, Trientalis europæa.*

*p*H 4·5 to 6·0 : *Melica uniflora, Milium effusum, Asperula odorata.*

*p*H 6·0 to 7·4 : *Hordeum sylvaticum, Mercurialis perennis, Allium ursinum, Aegopodium podagraria, Brachypodium sylvaticum, Ficaria verna, Geum urbanum, Anemone hepatica, Sanicula europæa.*

TABLE 98.—AVERAGE FREQUENCY [2] OF MEADOW SPECIES ON SOILS OF DIFFERENT *p*H VALUES. OLSEN (1923).

	3·5-3·9.	4-4·4.	4·5-4·9.	5-5·4.	5·5-5·9.	6-6·4.	6·5-6·9.	7-7·4.	7·5-7·9.	No. of Localities.
Deschampsia flexuosa . .	86	68	40	—	—	—	—	—	—	13
Calluna vulgaris	20	47	10	20	—	—	—	—	—	13
Gallium hercynicum . .	94	77	40	20	15	—	—	—	—	18
Potentilla erectum	67	99	63	73	48	45	10	20	—	39
Agrostis canina.	—	100	100	73	63	100	—	—	—	12
Festuca ovina .	—	100	47	35	20	20	50	—	—	12
Anthoxanthum odoratum .	33	47	79	80	83	76	27	30	30	46
Deschampsia cæspitosa . .	—	—	—	40	67	62	33	52	23	33
Circium oleraceum . .	—	—	—	—	—	—	50	100	80	8
Angelica sylvestris . .	—	—	—	—	—	35	33	48	30	14
Tussilago farfara	—	—	—	—	—	10	10	55	80	9
Agrostis alba .	—	—	—	—	—	—	30	65	60	7

Striking examples are found on undisturbed grassland. The Rothamsted grass plots are of varying degrees of acidity ;

[1] A remarkable plant association in the Tatra region is described by T. Wąsowicz, *Polska Akad. Umiej., Prace Roln. Lesne,* Cracow, 1933, No. 7. *Pinetum mughi* has its lowest limit at *p*H 3·2 and its greatest frequency between *p*H 3·7 and 3·9.

[2] The frequency is determined on ten trial areas (0·1 sq. metre) at each centre chosen. If a plant is found on eight of these areas at one centre, the frequency is 80 per cent. The figures in the table are the average of the frequencies at all the centres.

some have been made strongly acid by long manuring with ammonium sulphate, while most of them have had lime applied to one half but not to the other. The resulting

TABLE 99.—INFLUENCE OF LIME ON *p*H VALUE AND HERBAGE OF ROTHAMSTED GRASS PLOTS: 1919 RESULTS.

	Plot 3.		Plot 7.		Plot 11.	
	No Manure.		Potassic and Phosphatic Fertilisers. No Nitrogen.		Complete Fertilisers. Heavy Dressings of Sulphate of Ammonia.	
	No Lime.	Lime.	No Lime.	Lime.	No Lime.	Lime.
*p*H of surface soil	5·72	6·88	5·43	6·68	3·79	4·13
*p*H of subsoil	6·16	6·58	5·90	6·24	4·35	4·71
Vegetation.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Agrostis vulgaris	8·34	1·53	5·38	2·01	1·65	0·94
Alopecurus pratensis	0·29	0·61	1·73	15·20	0·77	63·91
Anthoxanthum odoratum	6·97	3·06	3·55	0·45	0·02	0·14
Arrhena therumavenaceum	2·29	0·51	3·05	2·62	31·34	15·51
Avena flavescens	0·88	2·76	0·71	0·96	—	—
Avena pubescens	4·12	19·10	2·84	8·81	—	—
Briza media	1·95	8·89	—	—	—	—
Bromus mollis	—	—	0·05	0·60	—	—
Dactylis glomerata	8·34	7·35	21·52	18·57	0·19	5·66
Festuca ovina	6·68	5·01	7·11	5·39	0·08	0·01
Holcus lanatus	9·13	7·66	4·26	1·56	64·80	11·63
Poa pratensis	0·15	1·94	1·17	1·61	—	1·95
Poa trivialis	—	0·10	0·36	1·21	—	—
Lotus corniculatus	1·57	2·45	0·46	0·03	—	—
Lathyrus pratensis	0·88	1·23	7·11	19·53	—	—
Trifolium pratense	2·06	1·74	1·02	0·03	—	—
Achillea millefolium	1·57	1·84	6·30	0·96	—	—
Centaurea nigra	5·70	6·13	2·54	1·11	—	—
Conopodium denudatum	4·61	0·61	9·44	3·67	—	—
Heracleum sphondylium	—	—	4·16	1·56	—	0·05
Leontodon hispidus	6·87	1·53	—	—	—	—
Plantago lanceolata	18·93	11·95	1·32	0·50	—	—
Ranunculus spp.	0·39	2·55	1·93	3·98	—	—
Rumex acetosa	1·96	4·19	10·55	7·10	1·15	0·11
Poterium sanguisorba	5·70	3·06	—	—	—	—

differences in the herbage have been recorded in the monograph by W. E. Brenchley; [1] they vary in detail according to the treatment of the plots. Some are quoted in Table 99.

Bent grass (*Agrostis vulgaris*), *Anthoxanthum*, *Rumex*, *Plantago* and *Conopodium* are all common on the acid plots; after addition of lime they are partly replaced by *Alopecurus*, *Avena pubescens*, and *Poa pratensis*; *Lathyrus* also increases.

In hill pastures in Yorkshire the most striking result of correcting acidity by lime is to replace *Nardus* and *Luzula*, or on the better pastures, *Agrostis*, by *Festuca ovina*, *Trifolium repens*, and *Lotus corniculata*.[2] Perennial rye grass is not common on land with lime requirement exceeding 0·3 per cent., but wild white clover is less sensitive to acidity.

The ranges of acidity over which the common pasture plants usually occur are recorded by Atkins and Fenton [3] who also show in accordance with practical knowledge that, on a pasture area of varying acidity, sheep and cows graze closely on soils of *p*H 6·5 and they will graze on somewhat more acid sites but only rarely on soils of *p*H less than 5.

The influence of disease organisms in determining the vegetation characteristics of sour soils is well seen on cultivated land. *Plasmodiophora brassicæ* (finger-and-toe organism) tolerates "sourness" better than its host plants the cultivated brassicas (swedes, turnips, cabbage, etc.); it is therefore injurious on sour soils. Addition of lime improves the soil for the crop but makes it less suited to the parasite [4] (Table 100).

[1] *Manuring of Grassland for Hay*, Rothamsted Monographs (Longmans, 1924). The figures are percentages of the air-dried hay. The mark — indicates absence of the species. Some minor species are omitted from the table.

[2] J. C. and D. A. Lynn, *Ann. Appl. Biol.*, 1924, **11**, 135. For studies of Welsh hill pastures see *Univ. Coll. Wales Plant Breed. Sta.*, Bull. H, No. 14, 1936, and for the Scottish hill pastures see W. G. Smith, *Scot. J. Agric.*, 1918, **1**, 261: see also W. G. Smith and C. B. Crampton, *J. Agric. Sci.*, 1914, **6**, 1.

[3] *Sci. Proc. Roy. Dublin Soc.*, 1930, **19**, 533.

[4] For field trials see J. Hendrick, *Trans. Highland Agric. Soc.*, 1918, Ser. 5, **30**, 137.

TABLE 100.—*p*H VALUES FOR PAIRS OF COMPARABLE SOILS DIFFERING AS HABITATS FOR PLANTS OR MICRO-ORGANISMS. E. M. CROWTHER, *J. Agric. Sci.*, 1925, **15**, 201.

Centre.	Crop.	Condition.	*p*H.	Condition.	*p*H.
(1) Rothamsted	Swedes	Finger-and-toe	5·85	No finger-and-toe	7·90
,,	,,	,, ,,	6·05	,, ,, ,,	7·87
(2) Garforth .	,,	,, ,,	5·66	,, ,, ,,	6·13
(3) Aberdeen .	Turnips	Much finger-and-toe	6·21	Little finger-and toe	7·13
(4) Somerset .	Barley	Failure	4·41	Good	5·77
(5) Ipswich .	Lucerne	,,	6·15	,,	7·86
(6) Carrington[1]	—	Uncultivated	3·01	Cultivated	5·52
Moss .	—	Bad field	4·88	Good field	5·14
(7) Pusey .	Potatoes	Much scab	7·40	Little scab	6·13
	,,	,,	7·65	,,	6·75

On the other hand, *Actinomyces chromogenus* (*Oospora*), potato scab, is less tolerant of sourness than its host, and over a certain range potatoes can be grown well without fear of attack. Even though their soils need lime for other crops, Cheshire farmers do not add it until after the potatoes are lifted, otherwise "scab" may develop. More acid soils need lime for potatoes, but care must be exercised in applying it or "scab" results. The fungus causing "Take-all" in wheat (*Ophiobolus graminis*) develops much more readily in slightly alkaline than in acid conditions: it is liable to do damage on calcareous soils but not on slightly acid sands on heavy loams.

"Deficiency" diseases are also affected by soil reaction: the "grey fleck" disease of oats due to lack of manganese (p. 104) is less common in acid than in neutral conditions.

The effect on the general soil population is discussed on page 467.

There has been much discussion as to the actual cause of the injury to plants on acid soils. Three possibilities have been studied:—

(1) *Direct Injury by the Acid* (*i.e. the Hydrogen*) *Ions.*—This view is adopted by many workers, *e.g.* C. Olsen. A

[1] These soils have been discussed by E. Price Evans, *J. Ecol.*, 1923, **11**, 64.

difficulty in the way of accepting it is that the *p*H values of acid agricultural soils rarely fall below 5, which is less acid than many good water culture solutions. The solution successfully used for barley at Rothamsted has a *p*H 3·8, yet on the field plots at Woburn barley fails when the *p*H has fallen only to 5·0.

The two cases are not strictly comparable, however. The *p*H value recorded for a soil is really that of a suspension in water (usually 1 in 5) and as dilution raises the *p*H, the value is higher than that of the soil solution in contact with the root. Further, the soil is highly buffered while the solution is not; in absorbing its nutrients the plant brings about certain changes which lower the acidity of the solution, changing it to neutrality or even alkalinity, but the same effect may not be produced in the highly buffered soil.

(2) *Soluble aluminium compounds* resulting from the acidity of the soil are regarded by Hartwell and Pember [1] of Rhode Island as the chief toxic agents; this view is accepted at the New Jersey Experiment Station,[2] at other centres in the United States, in Hawaii, and by some of the Indian tea experts.[3] It is, however, rejected by Olaf Arrhenius in his surveys of the Swedish soils, except perhaps for barley,[4] by O. C. Magistad at Wisconsin,[5] and by Olsen who, however, also excepted barley.

(3) *Lack of calcium* is probably a very important factor, for there are many instances where low *p*H values are tolerated so long as sufficient calcium is present. G. W. Robinson considers that calcium starvation is the chief factor in North

[1] *J. Amer. Soc. Agron.*, 1918, **10**, 45.

[2] A. W. Blair and A. L. Prince, *Soil Sci.*, 1923, **15**, 109.

[3] W. T. McGeorge, *Hawaiian Sugar Planters' Expt. Sta. Bull.* No. 49, 1925; P. H. Carpenter and C. R. Harler, *Indian Tea Assoc. Sci. J.*, 1921, 43. See also N. M. Comber, *Trans. Faraday Soc.*, 1924, 567; K. Miyake and I. Tamachi, *J. Biochem.*, Tokyo, 1924, **3**, 305.

[4] *Ztschr. Pflanz. Düng.*, 1925, A, **4**, 348. See also his *Kalkfrage, Bodenreaktion und Pflanzenwachstum*, Leipzig, 1926.

[5] *Soil Sci.*, 1925, **20**, 181.

Wales. The upland soils, where acidity is most harmful and lime most beneficial, are poor in exchangeable CaO (usually less than 0·05 per cent.); the valley soils are also acid but contain 0·2 to 1 per cent. or even more of exchangeable CaO and do not respond to more. Morley Davies also gives examples of paleozoic soils of *p*H 5·8, but containing 0·65 per cent. exchangeable CaO which do not respond to lime; de Silva furnishes other examples.[1]

The second group of plants, growing better in acid than in neutral or alkaline conditions, have been much investigated; it includes lupins and heaths, the so-called calcifuges. Probably the determining factor is not preference for acidity but intolerance of calcium. M. Hinchliff and J. H. Priestley [2] show that the metabolism of *Calluna*, like that of other plants commonly occurring on badly aerated peat moors, characteristically produces exceptionally large quantities of fatty substances in the form of fat deposits, cuticle, secondary endodermis, etc., which are presumed to be of great advantage in peat conditions. It is suggested that calcium would tend to form insoluble soaps with these fats, thus choking up the tissues just behind the growing point and interfering also with the water supply. M. C. Rayner [3] has shown that the determining factor is neither the physical conditions nor an adverse effect on the Mycorrhiza on which the plant is dependent.

The Action of the Growing Plant on the Soil and on the Soil Organisms.

The growing plant is profoundly modified by the soil, and in turn the soil is modified by the plant. The removal of water by transpiration, and of soluble salts by assimilation, the evolution of carbon dioxide from the roots, and the additions of organic matter resulting from photosynthesis, translocation, and ultimate mingling with the soil, all affect the soil and the soil micro-organisms. Starting from the same mineral

[1] B. L. T. de Silva, *J. Ecol.*, 1934, **22**, 532.

[2] *Naturalist*, July, 1924, p. 201.

[3] *Ann. Bot.*, 1915, **29**, 97.

constituents four different soils may arise, according as the land is left for a sufficient period in deciduous forest, coniferous forest, grassland and arable land.

The various actions have been described in the preceding pages in sufficient detail: it is necessary now only to recapitulate them briefly.

The transpiration by the plant, and the retention of moisture by the organic matter in the upper layers, both reduce the amount of leaching. These factors are at a minimum under coniferous forest, and here, if the soil is sufficiently porous, leaching is at a maximum, the calcium tends to be washed out, the surface soil becomes acid and podzolisation sets in. Under deciduous forest or grassland there is much less leaching and also considerable return of leached substances, notably calcium and potassium, to the surface, so that the surface soil tends to remain more nearly neutral and a brown or black earth type of soil tends to form (p 280).

The interactions between the roots of growing plants and the soil affect the availability of the plant nutrients. Wallace has shown[1] that chlorosis of fruit trees is more common where the soil is kept free from other vegetation than where grass or even weeds are allowed to grow. The leaves of the trees do not contain more iron as the result of the growth of the grass, but apparently it is more mobile and more available for chlorophyll formation. They contain, however, considerably more calcium, though less potassium at any rate where the supplies of potassium are adequate (Table 101). The grass also increases the availability of the potassium in the soil and can thus remedy potassium deficiency.[2]

Plant roots have an important mechanical effect on the subsoil: some deep rooting plants can force a way even through a hard subsoil. Advantage is taken of this property

[1] Long Ashton Ann. Repts.

[2] The fact has been observed by others, and has been attributed solely to a reduction of the nitrate uptake by the tree, and therefore of the N/K ratio in the leaves.

TABLE 101.—EFFECT OF GRASS GROWING AROUND APPLE TREES. WALLACE.

Effect on Chlorosis (*J. Pomol. and Hort. Sci.*, 1928, **7**, 251).

Cultural Treatment since August, 1925.	No. of Trees Recorded.	Chlorosis Markings. Averages per Plot. July, 1926.
Clean cultivation. . .	163	1·75 = Medium
,, ,, . . .	60	1·54 = Slight to medium
Tumbledown grass and wild white clover . . .	565	0·74 = Trace to slight
Tumbledown grass and weeds	30	0·60 = Trace
Lucerne	148	0·52 = Trace

Effect on composition of mineral substances in leaf.
(*Private communication.*)

Condition of Tree.	Culture.	Ash in Dry Matter, Per Cent.	Percentage Composition of Ash.				
			CaO.	K_2O.	Fe_2O_3	MgO.	P_2O_5
Chlorotic .	Arable	8·27	12·31	39·32	0·34	7·08	10·28
Green .	Grass	7·16	20·20	31·11	0·33	8·32	9·40

to deepen the surface soil in temperate climates, and to facilitate drainage in irrigated soils or those in wet, tropical conditions. Lupins have been used in Germany for bringing into cultivation sandy soils underlain by a pan (p. 338), and lucerne and sweet clover are both used in irrigated regions where a hard compact layer underlies the surface and impedes drainage. Tree roots are used in the tropics; Mann [1] recommends *sau* trees (*Albizzia stipulata*) for Assam, where a good forest soil a few inches deep rests on an intractable subsoil.[2]

A further important mechanical effect of the growing plant is that its fibrous root system has a binding effect on the soil. This is illustrated particularly well when the soil is continuously cultivated so that the organic matter is burnt

[1] "Tea Soils of N.E. India," *Indian Tea Assoc.*, Calcutta, 1907.
[2] For other examples see *Imp. Bur. Soil Sci. Tech. Com.* No. 22, 1931.

out: the soil then falls to a powder and becomes very liable to erosion (p. 576).

The only certain remedy is to re-establish a cover of vegetation, but this is often very difficult.

Considerable changes in the plant nutrients of the soil are effected where the crop is regularly removed as in agriculture.

Different plants vary greatly in the relative amounts of nutrients they absorb even when grown under similar conditions. English data assembled by Warington are set out in Table 102; extensive German data giving not only the final amounts but also the amounts taken at the various stages of growth are published by Wilfarth, Römer, and Wimmer (1905). Cereals absorb less nutrients than any of the other crops studied; as shown in the Table their total production of dry matter is approximately the same as that of red clover, hay, and swedes, and greater than that of meadow hay and beans, yet they take from the soil only half the nitrogen and potassium and only one-third of the calcuim. Clover takes up large amounts of potassium, calcium, and magnesium, while mangolds take much greater quantities of nitrogen, potassium, sodium, magnesium, phosphoric acid, and chlorine than any other crop. The figures for potatoes are incomplete, but recent data suggests that the amounts of these particular substances left in the haulms are only small.

Another effect of the growing plant on the soil is to alter its reaction. This depends partly on the relative amounts of calcium absorbed from the soil, partly also on the excretion of CO_2 from the plant roots. Striking results are obtained at the Rhode Island Station where the mangolds take up so much calcium and magnesium that they increase the acidity of the soil and its content of soluble aluminium salts with considerable detriment to succeeding crops, sensitive to acidity, such as onions; red top (*Agrostis alba*), on the other hand, takes less calcium and causes less injury.[1]

[1] For summaries see B. Hartwell, *J. Amer. Soc. Agron.*, 1927, **19**, 255; and P. S. Burgess, *R.I. Agric. Expt. Sta. Bull.* No. 198, 1924.

TABLE 102.—AMOUNTS OF VARIOUS SUBSTANCES ABSORBED FROM THE SOIL BY THE COMMON AGRICULTURAL CROPS OF ENGLAND. WARINGTON.[1]

	Weight of Crop.		Total Pure Ash.	Nitrogen.	Sulphur.	Potash.	Soda.	Lime.	Magnesia.	Phosphoric Acid.	Chlorine.	Silica.
	At Harvest.	Dry.										
	lb.	lb.	lb.	lb.	lb.	lb.	lb.	lb.	lb.	lb.	lb.	lb.
Wheat, grain, 30 bush.	1,800	1,530	30	34	2·7	9·3	0·6	1·0	3·6	14·2	0·1	0·6
,, straw	3,158	2,653	142	16	5·1	19·5	2·0	8·2	3·5	6·9	2·4	96·3
Total crop	4,958	4,183	172	50	7·8	28·8	2·6	9·2	7·1	21·1	2·5	96·9
Barley, grain, 40 bush.	2,080	1,747	46	35	2·9	9·8	1·1	1·2	4·0	16·0	0·5	11·8
,, straw	2,447	2,080	111	14	3·2	25·9	3·9	8·0	2·9	4·7	3·6	56·8
Total crop	4,527	3,827	157	49	6·1	35·7	5·0	9·2	6·9	20·7	4·1	68·6
Oats, grain, 45 bush.	1,890	1,625	51	34	3·2	9·1	0·8	1·8	3·6	13·0	0·5	19·9
,, straw	2,835	2,353	140	18	4·8	37·0	4·6	9·8	5·1	6·4	6·1	65·4
Total crop	4,725	3,978	191	52	8·0	46·1	5·4	11·6	8·7	19·4	6·6	85·3
Meadow hay, 1½ tons	3,360	2,822	203	49	5·7	50·9	9·2	32·1	14·4	12·3	14·6	56·9
Red clover hay, 2 tons	4,480	3,763	258	98	9·4	83·4	5·1	90·1	28·2	24·9	9·8	7·0
Beans, grain, 30 bush.	1,920	1,613	58	78	4·4	24·3	0·6	2·9	4·2	22·8	1·1	0·4
,, straw.	2,240	1,848	99	29	4·9	42·8	1·7	26·3	5·7	6·3	4·3	6·9
Total crop	4,160	3,461	157	107	9·3	67·1	2·3	29·2	9·9	29·1	5·4	7·3
Turnips, roots, 17 tons	38,080	3,126	218	61	15·2	108·6	17·0	25·5	5·7	22·4	10·9	2·6
,, leaf	11,424	1,531	146	49	5·7	40·2	7·5	48·5	3·8	10·7	11·2	5·1
Total crop	49,504	4,657	364	110	20·9	148·8	24·5	74·0	9·5	33·1	22·1	7·7
Swedes, roots, 14 tons	31,360	3,349	163	70	14·6	63·3	22·8	19·7	6·8	16·9	6·8	3·1
,, leaf	4,704	706	75	28	3·2	16·4	9·2	22·7	2·4	4·8	8·3	3·6
Total crop	36,064	4,055	238	98	17·8	79·7	32·0	42·4	9·2	21·7	15·1	6·7
Mangolds, roots, 22 tons	49,280	5,914	426	98	4·9	222·8	69·4	15·9	18·3	36·4	42·5	8·7
,, leaf	18,233	1,654	254	51	9·1	77·9	49·3	27·0	24·2	16·5	40·6	9·2
Total crop	67,513	7,568	680	149	14·0	300·7	118·7	42·9	42·5	52·9	83·1	17·9
Potatoes, tubers, 6 tons	13,440	3,360	127	46	2·7	76·5	3·8	3·4	6·3	21·5	4·4	2·6

[1] The yields quoted are not averages, though they are commonly obtained on farms.

Seeing that all plants give off carbon dioxide from their roots it might be expected that all would make the soil acid. Apparently this does not necessarily happen : water cultures tend to become alkaline because the plant takes up the acid radicle of the sodium nitrate and leaves behind the base, which immediately appears as the carbonate. Hall and Miller [1] and subsequently Maschhaupt,[2] obtained evidence of a similar action in the soil, the calcium nitrate formed during nitrification being converted into calcium carbonate while the nitrate radicle is taken by the plant. This tends to increase the amount of calcium in the surface soil.

A. Koslowska [3] has studied the power of various wild plants to change the soil reaction. Those restricted to rather narrow *p*H ranges had a distinct power both of reducing the acidity of a medium that is somewhat too acid, and reducing the alkalinity of a medium that is a little too alkaline ; the sap extracted from these plants showed a high degree of buffering. The sap of plants with a wide range of tolerance was on the other hand only feebly buffered. *Vaccinium myrtillus*, which can tolerate high acidity (up to *p*H 3·8), had no power to " alkalise " an acid medium, though a very strong power to acidify an alkaline one. *Corydalis cava* on the other hand which is very restricted in its range (*p*H 6 to 7·5) has a marked power of " alkalising " but little power of acidifying a medium, while *Festuca sulcata*, characteristic of steppe associations on a calcareous substratum, had even greater " alkalising " power.

The growing plant has considerable influence on the soil micro-organisms. Numerous observers have found more bacteria on cropped than on fallow land.[4] Starkey [5] has shown that in cropped land the numbers of certain bacteria

[1] *Proc. Roy. Soc.*, 1905, B, **77**, 1.

[2] *Verslag. Landb. Onderzoek Rijkslandbouwproefstat.*, 1911, **10**, 50.

[3] *J. Ecol.*, 1934, **22**, 396.

[4] Among them C. A. LeClair, *J. Agric. Res.*, 1915-1916, **5**, 439, and Greaves, Stewart, and Hirst, *ibid.*, 1917, **9**, 293.

[5] *Soil Sci.*, 1929, **27**, 319, 355, and 433.

were increased in the neighbourhood of the plant roots, as also was the evolution of CO_2 and the rate of production of nitrate: this effect was only slight in the early life of the plant but increased as the plant reached full growth; it was greater for biennials which continue growing than for annuals. Rape showed it in a marked degree, potatoes much less.

The total amount of nitrate present in cropped soils, however, is less than that in adjoining fallow soils even when allowance is made for the quantity absorbed by the plant. The fact has been observed at Rothamsted (Table 103), at

TABLE 103.—NITROGEN AS NITRATES IN CROPPED AND UNCROPPED SOILS.

(*a*) AT ROTHAMSTED. RUSSELL (*J. Agric. Sci.*, 1914, **6**, 18-57).

	June, 1911.		July, 1912.	
	Fallow Land.	Cropped Land.	Fallow Land.	Cropped Land.
N as nitrate in top 18 in. of soil (June)	54	15	46	13
Nitrogen in crop, lb. per acre	—	23	—	6
Total lb. per acre	54	38	46	19
Deficit in cropped land, lb. per acre	—	16	—	27
Expressed as N, parts per million.				
N as nitrate 0 to 9 in. depth	12	4	8	2
9 to 18 in. depth	9	2	10	3

(*b*) AT ITHACA, N.Y. LYON AND BIZZELL (*Cornell Agric. Expt. Sta. Mem.* 1, 1913.)

PARTS PER MILLION.

1908.	Fallow Land.	Land Carrying Maize.	1909.	Fallow Land.	Land Carrying Oats.
May 19	4·9	3·9	April 22	19·0	10·9
June 22	10·9	9·3	June 24	12·6	2·5
July 6	14·5	14·2	July 12	12·5	1·0
July 27	42·1	43·2	August 7	18·4	0·8
August 10	40·3	37·3	—	—	—

Grignon,[1] at Ithaca, in India,[2] and in Egypt.[3] Under these widely varying climatic conditions it can hardly be attributed to the minor differences in temperature and moisture content between cropped and uncropped soils. The fact of crop interference with nitrate accumulation was first observed in 1905 by Warington ;[4] the Broadbalk drainage waters contained less nitrate than was expected from the manure applied and the crop reaped, a result he attributed partly to denitrification and partly to some obscure interaction between the plant and the nitrate. T. L. Lyon, J. A. Bizzell, and B. D. Wilson [5] found that potatoes, wheat, and oats interfered with nitrate accumulation ; maize also did so in its later stages of growth but not in its earlier. They put forward a view which satisfactorily reconciles the lessened nitrate accumulation with high bacterial numbers : they suppose that the roots exude some organic matter, or shed dead residues which induce multiplication of bacteria that consume nitrate [6]

Interactions between Growing Plants.

Effects of Plants on their Successors.

A persistent idea that one crop may poison another is current among practical men. Early in the last century de Candolle formulated the hypothesis that plants excrete from their roots toxins that remain in the soil for some time and injure other plants of the same species, but not necessarily plants of different species. He thus explained the well-known fact that a rotation of crops is more effective than a system

[1] Dehérain (1892).

[2] J. W. Leather, *Mem. Dept. Agric. India*, Chem. Ser., 1912, **2**, 63.

[3] J. A. Prescott, *J. Agric. Sci.*, 1919, **9**, 216, and 1920, **10**, 177.

[4] *Trans. Highl. Agric. Soc. Scot.*, 1905, Ser. 5, **17**, 148.

[5] *J. Amer. Soc. Agron.*, 1923, **15**, 457, also Lyon, *ibid.*, 1918, **10**, 313.

[6] The multiplication was proved by J. K. Wilson and T. L. Lyon, *Cornell Agric. Expt. Sta.*, Mem. No. 103, 1926.

of continuous cropping; in a rotation the toxin excreted by a particular crop is innocuous to the succeeding crop and disappears from the soil before the same plant is sown again.

The hypothesis was tested in a classical research by Daubeny at Oxford (1845), but could not be justified. Eighteen different crops were grown continuously on the same plots, and the yields compared with those obtained when the same crops were shifted from one plot to another, so that no crop ever followed another of the same kind. No manure was supplied. The results showed a gradual decrease in the yield in almost every instance, and the decrease was generally greater when the crop was repeated year after year on the same plot than where it was shifted from one to another. Nevertheless the difference between the yields in the two cases was not sufficient to justify any assumption of the existence of a toxin, except perhaps in the case of *Euphorbia lathyris;* in the other seventeen cases it was attributed to the more rapid removal from the continuous plots of the mineral nutrients required by the plant. This explanation was supported by analyses of the plant ash and of the soil—analyses which led to the important distinction between "available" and "unavailable" plant food.

Pot experiments made by the writer at Rothamsted led to the same conclusions. No evidence exists of any lasting toxic effect produced by one crop on its successor.

Agriculturists have, however, found by experience that crops grow better in rotation than in continuous succession. It is true that continuous cropping is possible: the Broadbalk wheat field at Rothamsted has already produced more than ninety crops of wheat in succession and the Woburn Stackyard field produced more than fifty; but it is more difficult to secure good yields than on the rotation field where wheat is grown only once in four years, other crops being taken in the intervening years (Table 104). Manures gradually lose some of their effectiveness on the continuous plots, tending especially

TABLE 104.—WHEAT GROWN WITHOUT MANURE AT ROTHAMSTED: (1) GROWN CONTINUOUSLY; (2) IN ALTERNATION WITH FALLOW; (3) IN FOUR-COURSE ROTATION. AVERAGE FOR THE YEARS 1851 AND EVERY FOUR YEARS THEREAFTER UNTIL 1927.

Dressed Grain per Acre.		
Continuous Wheat (Broadbalk, Plot 3).	Wheat after Fallow (Hoos Field, Plot 0).	Rotation Wheat (Agdell Field, Plot 5) formerly 21-22.
Bushels	Bushels	Bushels
11·3	14·0	24·0

after long periods of years to produce less increment of crop.[1]

These differences do not continue to show indefinitely, however: after a time the yields on the rotation plots also fall.

Leguminous plants are specially affected: red clover, for example, can rarely be grown on the same land more frequently than once in four years.

The practical man, naturally anthropocentric in his outlook, speaks of land becoming "sick" and supposes that soil, like ourselves, benefits by a change. The Rothamsted field experiments afford the best data on the subject, and show that continuous cropping with the same crop is attended by many difficulties:—

(1) It is usually accompanied by uniformity in cultivation operations which may have harmful effects on the soil. Repeated ploughing to the same depth may form a hard layer or plough sole which interferes with root action; in a rotation this is less likely to happen as the depth of ploughing is varied at least once in three or four years.

(2) It favours the persistence of weeds specially adapted to live among the crop. The Broadbalk wheat field at

[1] See *Fifty Years of Field Experiments at the Woburn Experimental Station*, by E. J. Russell and J. A. Voelcker, with a Statistical Report by W. G. Cochran (Rothamsted Monographs, Longmans, 1936).

Rothamsted is badly infested with slender foxtail (*Alopecurus agrestis*), poppies (*Papaver rhœas*), and in places colts-foot (*Tussilago farfara*). The rotation fields are much less affected by weeds, as the intervening year in root crops affords opportunities for their extermination.

(3) It favours also the persistence of diseases and pests, especially those that can survive only a short time in the soil or that can find alternative hosts in close proximity.[1]

This is of particular importance for flax, sugar beet, and potatoes when parasitic nematodes begin to appear, and cereals on calcareous soils when "Take-all" or Whiteheads (*Ophiobolus graminis*) and Foot rots (*Fusarium spp.*) are present.

(4) It allows no opportunity of maintaining the organic matter in the soil such as is given by the clover or "seeds mixture" of a normal rotation. The effect of this is well shown in the Agdell rotation field, half of which carries clover once in four years while the other half does not (Table 105) :—

TABLE 105.—CROPS GROWN UNDER TWO ROTATIONS, ONE INCLUDING CLOVER EACH FOUR YEARS, THE OTHER NOT. AGDELL FIELD, ROTHAMSTED.

Average Produce per Acre (*Years from* 1848-1930).

Manuring.	Clover Hay.	Wheat, Total Produce.		Roots.		Barley Grain.	
		After Clover.	After Fallow.	After Clover.	After Fallow.	After Clover.	After Fallow.
	cwt.	lb.	lb.	cwt.	cwt.	bu.	bu.
None .	27·1	3533	3695	8·0	18·7	13·2	15·9
Minerals only	52·3	5245	4690	196·6	159·4	23·9	18·3
Minerals + nitrogen .	52·6	4863	4797	267·6	339·6	29·4	22·5

(5) When the cultural system involves some special condition, as on sewage farms, or glass-houses maintained at high temperature and humidity, disease organisms accumulate and

[1] See H. L. Bolley, *N. Dak. Agric. Expt. Sta. Bull.* No. 107, 1913.

the micro-organic population alters and may become less effective in producing plant food.[1]

These five effects appear to explain the differences between the yields of rotation and of continuous crops, and the general phenomena of " sickness " in soils.

The glass-house problem is of such technical importance that it has been investigated in detail by E. J. Russell and F. R. Petherbridge,[2] and methods of treatment worked out based on partial sterilisation of the soil. These have proved so effective that heating by steam or treatment with poisons (usually cresol) has become a recognised practice in the Lea Valley; the investigation is being continued at Rothamsted and at the Cheshunt Experimental Station,[3] where also the effect of the disappearance of the turf residues is studied.

Effects of Plants on other Plants Growing along with them.

(*a*) *Non-leguminous Plants.*—Pickering (1903) found at Woburn—and the observation has since been confirmed elsewhere—that the effect of growing grass round apple trees is to arrest healthy growth and to stunt the tree. The leaves become unhealthy and light coloured, the bark also becomes light coloured, while the fruit loses its green matter and becomes waxy yellow or brilliant red. Where the grassing was done gradually the trees accommodated themselves somewhat to the altering conditions, but never grew so well as when grass was absent.

This effect might have been due to various causes: changes in aeration, temperature, water supply, food supply, or physical condition of the soil; but careful experiments failed to show

[1] See H. von Bronsart, *Naturwissenschaften*, 1933, **21**, 310, for a review of biological causes of soil sickness not conditioned by chemical or physical influences.

[2] *J. Agric. Sci.*, 1912, **5**, 86; *J. Bd. Agric.*, 1912, **18**, 809; 1913, **19**, 809; 1914, **21**, 97.

[3] *Cheshunt Ann. Repts.*, 1917 onwards, also W. F. Bewley, *Bull. Min. Agric.*, 1931, No. 22.

that any of these factors came into play. Covering the soil with cement excluded air at least as thoroughly as grass, and yet did not produce the grass effect, nor was the effect suppressed by wet seasons, liberal watering, or a supply (in pot experiments) of sufficient water or nutrient solution to keep the soils of grassed and ungrassed trees equally moist, or equally well supplied with food. On the other hand, the grass effect was produced when perforated trays of sand containing growing grass were placed on the surface of the soil in which trees were growing, so that the washings from the grass went straight down to the tree roots. There seemed no possibility of the grass roots in the trays abstracting anything from the soil, and the only explanation appeared to be that a toxin was excreted by the grass.

Other plants behaved in the same way. Pickering therefore concluded that toxins are produced by all growing plants. He was unable to discover their chemical properties, except that they must be very unstable, because no toxic properties could be detected either in soil that had been removed from the grass roots or in the washings from the above-mentioned trays. Further, there was no recognisable difference between one plant toxin and another: injury resulted whatever crops were grown in the pots and trays, and it was not confined to plants of the same kind as supposed by de Candolle.

On Pickering's view one growing plant may, and usually does, injure others growing alongside of it, but injury is only during its lifetime and ceases with its death. The toxin is transient and not permanent; it is produced by the plant in any soil whether fertile or not.

Wallace has since shown that part at any rate of the harmful effect of grass on fruit trees is due to their vigorous absorption of nitrate, leaving nothing for the tree. But there still remains in Pickering's observations a good deal that has not been cleared up.

This removal of soil nitrate, with consequent diminution of crop, may explain some of the supposed toxic effects

that have been recorded. Achromeiko [1] found that a second sowing of oats gave a poorer yield than the first, but attributed this to the assimilation of most of the available plant nutrients, especially the nitrogen, by the bacteria decomposing the residues of the first crop. Sorghum ploughed into the soil in the semi-arid Western States is said to cause injury to the next crop, but it is also claimed to reduce, not to increase, bacterial action.[2]

Whitney (1906) supposed that organic toxic substances were widely distributed in natural soils, but there is no evidence for this.

(*b*) *Leguminous Mixed with Non-Leguminous Plants.*—There is some evidence that during the growth of certain leguminous plants, nitrogen compounds are excreted from their roots, and from these compounds adjacent plants can in certain circumstances benefit. Plants in sand culture make better growth in association with leguminous than with non-leguminous vegetation.

The evidence has recently been summarised by Hugh Nicol.[3] The early experiments of J. G. Lipman and of Lyon and Bizzell, showed that a non-leguminous crop such as oats grown in pots along with a leguminous one, field peas, made better growth than when there was no leguminous crop growing. It was assumed that the leguminous plant must somehow have furnished nitrogen compounds to its neighbours, but the process was not at all clear. Virtanen in Finland has recently re-examined the whole subject and shown that leguminous plants grown in sterile sand, but inoculated with the proper organisms, excreted from their roots marked quantities of soluble nitrogen compounds which seemed to be mostly amino-acids, with small quantities of basic nitrogen compounds, not, however, free ammonia.[4]

[1] *Landw. Jahrb.*, 1931, **74**, 713.

[2] J. F. Breazeale, *J. Amer. Soc. Agron.*, 1924, **16**, 689. Any sugar present would produce these effects (p. 389).

[3] *Int. Rev. Agric.*, 1936, **27**, 201T; also *Biol. Reviews*, 1934, **9**, 383.

[4] A. I. Virtanen, *Ann. Acad. Sci. Fenn.*, 1933, A, **36**, No. 12; A. I. Virtanen and S. von Hausen, *Ztschr. Pflanz. Düng.*, 1931, A, **21**, 57;

Some of Virtanen's experiments suggest that there may be as much nitrogen excreted as is retained in the plants.

The excreted nitrogen can at least in part be taken up by non-leguminous crops growing along with the leguminous crops. Using mixtures of peas and oats, the best results were obtained when there were about two oat-plants to one pea plant: when the oats were more numerous, the peas suffered from competition; they were dwarfed, and excreted less nitrogen so that the oats in turn suffered.

H. G. Thornton and Hugh Nicol at Rothamsted [1] have confirmed the general result. Italian rye grass grown in admixture with lucerne but without nitrogenous fertiliser contained 2½ times as much nitrogen as grass similarly grown by itself without lucerne. When a little nitrate of soda was added the difference was even more marked, and after 18 weeks, grass grown with lucerne contained nearly 6 times as much nitrogen as was added as nitrate. But when larger amounts of nitrate of soda were given, the benefit due to the lucerne fell off, because of the adverse effect of nitrate of soda on the activities of the nodule organisms. These experiments were all made in sand.

The results obtained in soil are different. In field experiments at Rothamsted with mixtures of oats and vetches the presence of vetches reduced the yields of oats and the quantity of nitrogen they contained: conversely the oats reduced the yield of vetches. In absence of nitrogenous fertiliser the total amount of produce per acre, however, was larger for the mixtures than for the pure crops indicating that the two crops had been able to grow somewhat but not entirely independently of each other. Where nitrogenous fertiliser was supplied, even this advantage was lost (Table 106).

with H. Karström, *Biochem. Ztschr.*, 1933, **258**, 106. Some results are summarised in *Herb. Reviews* (Aberystwyth), 1933, **1**, 88, and in *Chem. and Ind.*, 1935, **13**, 1015. The amino-acid-N has recently been shown by Virtanen and T. Laine to be 98·4 per cent. of the total excreted nitrogen: this corrects earlier results.

[1] H. G. Thornton and Hugh Nicol, *J. Agric. Sci.*, 1934, **24**, 269 and 540.

TABLE 106.—YIELDS OF DRY MATTER OF NITROGEN CONTENT OF OATS AND VETCHES GROWN SINGLY AND IN COMBINATION. (*Rothamsted Ann. Rept.*, 1932, p. 148.)

	4 Oats, 0 Vetches.	3 Oats, 1 Vetch.	2 Oats, 2 Vetches.	1 Oats, 3 Vetches.	0 Oats, 4 Vetches.
Total dry matter.	Cwt. per Acre.				
Oats—					
Without nitrogen .	42·9	36·6	30·5	21·7	—
With nitrogen . .	53·5	44·4	41·0	26·0	—
Vetches—					
Without nitrogen .	—	11·0	18·4	23·9	28·6
With nitrogen . .	—	8·6	14·9	19·1	30·9
Total dry matter.					
With nitrogen . .	42·9	47·6	48·9	45·6	28·6
With nitrogen . .	53·5	53·1	55·8	45·2	30·9
Percentage Nitrogen in dry matter.					
Oats—					
Without nitrogen .	1·145	1·329	1·287	1·401	—
With nitrogen . .	1·158	1·197	1·247	1·361	—
Vetches—					
Without nitrogen .	—	2·702	2·725	2·865	3·061
With nitrogen . .	—	2·659	2·761	2·908	2·993

Each seeding unit was 50 lb. seed per acre. The dressing of nitrogen was 0·3 cwt. N as sulphate of ammonia per acre.

There is therefore an apparent discrepancy between the pot experiments and the field results which, however, is quite consistent with the possibility that both are right. Nitrogenous excretions from the roots of leguminous plants may occur in natural soil, but the non-leguminous plants in field conditions may be unable to utilise them, because they are rapidly assimilated by micro-organisms.

Are Toxins present in the Soil?

There has been much discussion as to whether organic toxins accumulate in the soil causing a "staleing" of plant and bacterial growth, such as occurs in culture media with micro-organisms.

There is no evidence of the presence of soluble toxins in normally aerated soils sufficiently supplied with plant food and with calcium carbonate. Inorganic toxic substances, including hydrogen ions, soluble aluminium, iron and manganese

compounds, and organic substances, may occur on acid soils badly aerated and lacking in calcium carbonate, or on other exhausted soils.

There is no evidence of plant excretions conferring toxic properties on the soil, but the Woburn fruit-tree results show that a growing plant may injure its neighbour. The effect does not appear to be specific; any plant may be injured by any other within its range, but it may suffer more from one of its own kind than from one of another kind.[1]

Normal Conditions on a Heavy Soil.

Table 107 summarises many of the Rothamsted results and shows the conditions normally obtaining on a heavy soil in Hertfordshire under an annual rainfall of 28-30 inches.

TABLE 107.—CONDITIONS NORMALLY OBTAINING IN THE SOIL AT ROTHAMSTED.

Manurial Treatment of Soil.		Soil Moisture.[2] Per Cent. by Volume.	Soil Moisture.[2] Per Cent. by Weight.	Total Nitrogen. Parts per Million.	Total Nitrogen. Lb. per Acre.	Nitrogen as Nitrate. Parts per Million.	Nitrogen as Nitrate. Lb. per Acre.	Numbers of Bacteria. Millions per Gram.[3] Total (direct count).	Numbers of Bacteria. Millions per Gram.[3] Numbers growing on Plates.	CO_2 per Cent. by volume in Soil Air.
No manure	Cropped	23-12	15-8	990	2500	5-12	12-30 (top 9″)	1000	10	0·2-0·6[4]
Condition poor	Fallow	23	15			8-15	20-36			0·2-0·4
Farmyard manure	Cropped	30-15	17-8	2200	5000	10-20	25-50	3000	30	0·5-1·0[5]
Condition good	Fallow	30	17			20-5	50-84			0·2-0·6
Ordinary arable field . .	Cropped	25-12	15-8	1500	3700	10-15	25-36	2000	20	0·5-1·0[6]

[1] Thus H. Burmester (*Fühl. Landw. Ztschr.*, 1914, **63**, 547) claimed that couch (*Triticum* or *Agropyron repens*) increased the yield of oats, and W. E. Brenchley found that certain weeds had the same effect on the yield of wheat *per plant* (*New Phytol.*, 1917, **16**, 53).

[2] The concentration of the dissolved matter is of the order of 0·2 per cent., and the osmotic pressure about 1 atmosphere.

[3] For other micro-organisms see pp. 451 and 456.

[4] Running on occasions up to 1·8.

[5] Occasionally up to 2·5.

[6] Occasionally up to 2·3.

CHAPTER VIII.

SOIL FERTILITY IN NATURE AND IN FARM PRACTICE.

Soil Fertility in Natural Conditions.

WITHIN short periods of time the flora of an area of land left entirely to nature appears to remain constant. Actually it is not necessarily so. Two groups of factors lead to change. As already shown (p. 546), growing plants act on the soil and somewhat alter its composition and structure, thereby slowly altering it as a habitat for plants. Further, new plants are always liable to come in by invasion from neighbouring areas. If the conditions enable them to grow sufficiently vigorously they establish themselves; if not they die out. The ensuing flora is the result of the competition of the various species for whatever water, food, and light is available, and of their power to tolerate the reaction and other conditions of the soil. Plants grow not because the conditions are eminently suitable but because they are more endurable for them than for their competitors.

The effect of these various factors is that the natural flora is usually slowly changing and there results a succession of plant communities.[1]

Ecologists group the various soil conditions under the general term "Edaphic conditions." For any particular soil these depend on :—

(1) Its composition.
(2) The climate.
(3) Its topography.
(4) Its profile.

[1] F. E. Clements, *Plant Succession, Carnegie Inst.*, Washington, Pub. 242, 1916.

The effect of composition has already been adequately discussed. The effect of the climate is threefold. Acting through geological time it has largely determined the composition of the mineral constituents of the soil through its influence on the disintegration and decomposition of the original rock (p. 245). In shorter periods of time it greatly affects the inorganic constituents by leaching and the organic matter through its influence on the plants from which the organic matter arose. Moisture, warmth, and aeration favour the development of a succulent vegetation which sheds easily decomposable leaves and stems on to the soil; earthworms and bacteria flourish and produce the normal decomposition products that make up "mild humus" and a fertile soil. Dryness encourages a narrow-leaved xerophytic vegetation, the leathery fragments of which mingle with the soil, but afford a very indifferent medium for the growth of earthworms and bacteria, so that little decomposition goes on. Wetness and lack of aeration favour other kinds of vegetation and decomposition, forming "mild humus" or "acid humus" according to the amount of calcium carbonate present.

Finally, the rainfall determines the amount of water reaching the soil, while the temperature, wind, etc., determine the amount evaporating from the surface.

The position of the soil—its aspect and elevation—affects its temperature, its water supply, and its composition, especially its reaction and its content of soluble matter.

Effect of Topography on Temperature, Water Supply, and Soluble Matter: Microclimate.

The temperature on sloping land is affected in two different ways. As a general rule the higher land is cooler than the lower, being more exposed to wind. But on clear nights, when heat lost by radiation from the earth's surface is not again returned by the clouds, the air near the surface cools considerably and rolls down the slope to the lowest level it can reach, being replaced by warmer air. Thus the low-lying

ground suffers from cold nights or even frost which the higher ground escapes. This fact is of considerable importance in fruit-growing districts; plantations are made above the low levels liable to these frosts though not so high up as to suffer from exposure to wind. It is also important in forestry, where the action is called "cold-air drainage"; Forrest Shreve [1] gives a striking example where the normal temperature gradient was completely reversed, and the valley temperature fell to a level only attained on the neighbouring ridges at a height of 2300 feet above it. For ordinary farm crops this factor is of less importance, but it operates in modifying the vegetation of wild land. Bracken suffers more from frost than heather and is therefore less likely to survive at levels where late frosts are common.

The movement of rain water in the soil tends to be vertically downwards, but it is always liable to disturbance by impervious layers in the subsoil. In general low-lying soils receive from higher ground a considerable amount of water which they lose only with difficulty by drainage. They are therefore moister than the higher soils and are more liable to become water-logged.

Godwin shows that, in Wicken Fen, the plant communities are determined far more by the water-logged condition in winter than by any deficiency of water in summer.[2] This accords with an observation by E. J. Salisbury. In an interesting survey of the changes in the flora of Hertfordshire he showed that nearly two-thirds of the eighty species that have decreased or become extinct since records began are natives of wet or moist habitats; the rest are mainly natives of waste land.[3] The drainage of England has obviously much affected its natural floras and faunas.

[1] *Plant World*, 1912, pp. 110-115.
[2] H. Godwin and F. R. Bharucha, *J. Ecol.*, 1932, **20**, 157.
[3] *Trans. Herts. Nat. Hist. Soc.*, 1924, **18**, 51.

Topography, Soil Reaction and Flora.

The water soaking through the soil from higher ground carries with it much calcium and other soluble material, thereby impoverishing the higher ground and causing it to become acid.

This soluble matter accumulates at the lower levels ; there is therefore a tendency for the lower land to contain more soluble matter, more exchangeable bases,[1] and to be more nearly neutral in reaction than the higher land ; further, it

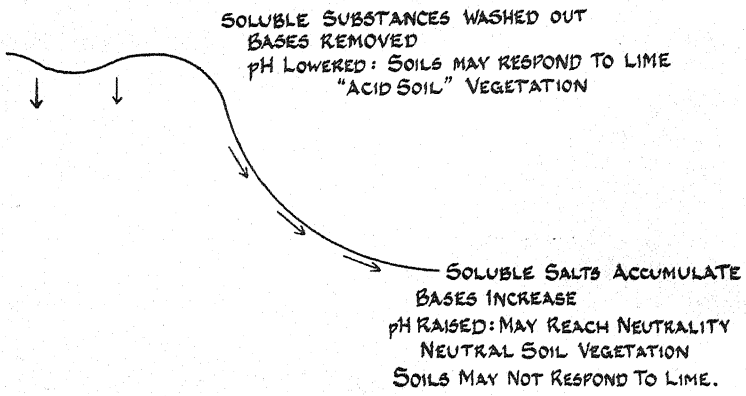


FIG. 62.—Diagram showing movements of water and soluble salts from the upland to the valley.

may not respond to dressings of lime (see p. 257). These differences are summarised in Fig. 62.

The aggregate effect on vegetation of these various actions is very marked. E. J. Salisbury [2] has studied a number of slopes in England that have been undisturbed by recent cultivation, and finds a strong tendency for a calcifugous flora to develop on the higher land, and a calcicolous flora on the lower.

[1] W. Swederski (*Puławy Mem.* 1933, 233). shows that where the drainage water does not easily get away the marsh soil becomes richer in absorbed calcium.

[2] *J. Ecol.*, 1922, **9**, 220 ; see also E. J. Salisbury and A. G. Tansley, *ibid.*, p. 19.

In the extreme case the upper land carried *Vaccinium* or *Calluna* and various species associated with them on acid soils, while the lower land carried *Mercurialis perennis*, *Allium ursinum* and the associated plants found on neutral soils. In less sharply contrasted conditions the sequence still holds. On Hudnall Common, one of the calcareous heaths of Hertfordshire, the surface soil at the summit had a *p*H value about 5·5 and carried a wild vegetation in which *Pteris* was dominant: at the bottom of the slope the *p*H of the soil was 7·5, and the vegetation a chalk pasture with scrub.

On a much smaller scale the effect is well illustrated by the successions of plant communities observed on the sand dunes at Blakeney Point where detailed observations on the vegetation and environmental conditions were begun by F. W. Oliver in 1910 and have been continued each year to the present time by the students of the Botany Department, University College, London. E. J. Salisbury [1] has recorded the successions. In their early stages the sand dunes contain calcium and are neutral. As they grow older some or all of the calcium carbonate is washed out, and the organic matter increases so that the dune becomes markedly acid and moister.[2]

The embryo dunes have on the whole a calcicolous flora, the older ones a calcifugous flora.

	$CaCO_3$.	Organic Matter per Cent.	Maximum Water Content per Cent. Weight.	*p*H.
Embryo dunes	0·4	0·4	25	6·9-7·4 (Av. 7·2)
Older dunes .	0·01	1·1	36	6·1-7·3 (Av. 6·4)

An interesting study of vegetation of the Chiltern Hills (Chalk) by A. S. Watt [3] affords a good illustration of the

[1] *Ann. Bot.*, 1922, **36**, 391.

[2] At Blakeney and at Southport the acid condition is attained in about 150-200 years; after this organic matter rapidly accumulates (*J. Ecol.*, 1925, **13**, 322).

[3] *Ibid.*, 1934, **22**, 230 and 445.

methods and results of modern ecological survey. Beechwoods are characteristic of the region but they are of several kinds. On the escarpment they fall into two groups, one associated with *Sanicula europea*, the other with *Mercurialis perennis*. The sanicle beechwood arose as the result of a succession : Grassland → juniper scrub → beechwood (sanicle).

For the mercury beechwood the succession was—

Grassland → hawthorn scrub → (Ashwood) → beechwood (mercury).

Both soils contained calcium carbonate fragments throughout their depth, but the sanicle beechwood was on the drier and the mercury beechwood on the moister soils : these latter were almost black to a depth of about 8 inches and could be classed as Rendzinas (p. 285).

On the plateau the soils were of two types : Brown earths and podzolised soils ; on the former the succession was—

Grassland → hawthorn and blackthorn scrub → developing woodland (ash-oak).

→ oakwood → beechwood ;

on the podzolised soil it was—

Grassland → (oakwood) → beechwood.

The *p*H of the brown earth types was 4·5-5 in the top 6 inches, rising to 5·8 at 6-9 inches, and falling at lower depths to 4·7. The values for the podzolised soil were 3·85 just below the surface layer of raw humus, and 4·6 lower down.

If it were not for invasion the oak would apparently be stable, since it tends to produce a brown earth eminently suited to it. Beech, however, is an effective invader, but it does not remain stable. It tends to produce a podzol and thus to form a heath. The ultimate end apparently tends to be :—

Beechwood → heath.

The Control of Soil Fertility.

The factors most usually brought under control are : Water supply ; Food supply ; Soil reaction ; Depth of soil ; Permanence of soil layer.

The food supply has already been discussed in Chapter II and the control of soil reaction in Chapter VII.

Control of Water supply: (1) Humid Climates.

In humid climates the water supply of the soil is controlled by—

(1) Addition to the soil of organic matter in the form of farmyard manure or crop residues.

(2) Occasionally in the past, but only rarely now, addition of clay. Sand is sometimes added to peat soils.

(3) Drainage.

(4) Cultivation.

The first two have been sufficiently discussed on pp. 194, 209.

Drainage.—In draining an area of land, ditches or trenches are cut along which the water can flow away to the river system. Where much water is involved and the land is cheap the ditches are often left open but they have to be properly maintained otherwise they are liable to be choked with weeds or their banks may fall in. Where less water is involved narrow trenches suffice and the water is then carried away by porous clay pipes laid without any cement joints, the trench being filled up again. An alternative method is to "mole-drain." A pointed cylinder is dragged through the soil at a depth of 9 to 20 inches below the surface: it cuts a tunnel along which the water can escape. Although there is no pipe, the tunnel stands for a long period, often 10 to 15 years, or more.

The drainage system has to be carefully planned in accordance with the contour of the land. The simple theories of soil drainage assume that the soil is perfectly homogeneous, and that the rain water falling on it percolates vertically downwards till it reaches the ground-water level. Then, when the ground water has risen above the drain level, it starts flowing into the drain at a rate which can be calculated according to the laws of hydrodynamics. Rothe,[1] using this method of

[1] J. Rothe, *Landw. Jahrb.*, 1924, **59**, 453.

approach, and making certain simplifying assumptions, obtained the formula—

$$h = \frac{E}{2} \cdot \frac{q}{k}$$

relating the height of the ground water above the drain level (h), the distance apart of the drains (E), the rate at which water enters the drains (q), and the soil permeability (k).

The formula has been experimentally verified by Diserens in certain drainage areas in Switzerland. It can be applied, however, only where the soil is uniform over a fairly wide area and where the subsoil is relatively impermeable.[1]

Flodkvist [2] measured the outflow rates from drainage systems in several heavy soils in Sweden, and found that they fluctuated much more violently than was to be expected on the simple theory given above. After heavy rain the rate generally rose rapidly to a very high maximum, and then fell almost equally rapidly to a much lower value, from which it gradually decreased to zero. He considered that this type of response could be explained most satisfactorily on the assumption that the undisturbed subsoil was almost impermeable and that the surplus water reached the drains by way of the disturbed soil vertically above the drains, which had been dug out and replaced when the system was constructed. He was able to show by experiment that the soil above the drain was in fact much more permeable than the undisturbed subsoil elsewhere in the field, even in very old systems.

The pore space in the disturbed subsoil vertically above the drains was found by Fauser [3] in Germany to be considerably greater than in the subsoil between the drains even after

[1] Diserens, *Trans. VI Comm. Int. Soc. Soil Sci.*, 1933, B, 188. See also J. Kozeny, *ibid.*, 1932, A, 42, and S. B. Hooghoudt, *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, 1, 397.

[2] H. Flodkvist, *Sverig. Geol. Unders. Årsb.*, 1931, Ser. C, **25**, No. 4. He gives a good summary table of his permeability results in *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **3**, 165-166.

[3] O. Fauser, *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, 1, 391.

25 years; he found also that the pore space throughout the whole drained area had increased to some extent as a result of drainage.

Nicholson [1] has measured the outflow rates from mole drains in a heavy soil at Cambridge, and has obtained curves which are very similar to those of Flodkvist. He has also shown that the form of the curves is determined to some extent by the nature of the soil, the type of cultivation, and the previous weather.[2]

In view of the complexity of the theory of soil drainage a number of empirical methods have been devised on the Continent for advisory purposes: those commonly used are based on one or other of the following properties:—

(1) Mechanical composition, usually expressed as the percentage of particles smaller than 0·01 mm. diam.[3] or else smaller than 0·002 mm. diam.[4]

(2) Hygroscopicity.[5]

(3) Heat of wetting.[6]

(4) Specific surface, calculated either from the mechanical composition or from the permeability of the soil.[7]

A number of empirical formulæ or curves have been put forward to express the relation between each soil type, as determined by one of the above methods, and the drain depth and distance apart which are considered by practical experience to be the best for that soil.[8]

[1] H. H. Nicholson, *J. Agric. Sci.*, 1934, **24**, 349.

[2] Fauser has summarised the more important recent work on soil drainage in *Trans. VI Comm. Int. Soc. Soil Sci.*, 1932, A, p. 128, and *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 388.

[3] J. Kopecky, *Die Bodenuntersuchung zum Zwecke der Drainagearbeiten*, Prague, 1901.

[4] F. Zunker, *Kulturtech.*, 1926, **29**, 9.

[5] Mitscherlich, *Bodenkunde für Land- und Forstwirte*, 4th ed., Berlin, 1923.

[6] H. Janert, *J. Agric. Sci.*, 1934, **24**, 136.

[7] F. Zunker, *Kulturtech.*, 1926, **29**, 9.

[8] Examples are given by F. Zunker, *Landw. Jahrb.*, 1921, **56**, 561; O. Fauser, *Meliorationen*, Berlin, 1921; and H. Janert, *Imp. Bur. Soil Sci., Tech. Comm.* No. 27, 1933.

The most generally used of these methods of classification have been compared with each other in two investigations carried out in Germany [1] and Finland [2] respectively. In both cases it was found that there was little to choose between the different methods, although both Zunker and Keso considered that the mechanical analysis gave a slightly more satisfactory classification than the hygroscopicity and heat of wetting. This advantage is offset, however, by the fact that the heat of wetting determinations are cheaper and more rapid—an important consideration where routine determinations must be made.[3]

Effects of Drainage.—Drainage allows of better entry of air into the soil by removing the excess of water. But rather paradoxically it also improves the distribution of water in the soil. A drained soil is not infrequently somewhat moister than an undrained one, especially in dry weather. This was brought out by the measurements of Thøgersen in Denmark.[4] In Siebert's experiments [5] the soil immediately above the drain was moister than that in between the drains, especially in heavy soils or during dry weather, a result that had already been obtained by Solnar in Czecho-Slovakia.[6]

The explanation put forward by Mezger [7] is that the drain pipe allows the escape of the soil air which otherwise, being

[1] F. Zunker, *Kulturtech.*, 1928, **31**, 39.

[2] J. Keso, *Valt. Maatalousk. Julk.*, No. 32, 1930.

[3] For a full discussion of the theory of drainage and of these various methods, see J. L. Russell, *J. Agric. Sci.*, 1934, **24**, 544.

[4] F. Thøgersen, 1930, *Foreløbig Beretning vedrørende Draeningsforsøget i Kvorning*, Viborg (Abstr. in *Trans. VI Comm. Int. Soc. Soil Sci.*, 1932, A, 155).

[5] Shown by K. Siebert at Konigsberg: "Die Wirkung von Dränungen auf die Struktur des Bodens," *Dissertation*, 1930. For a discussion of the relation between the rate of outflow from the drains and the height of the water table above drain level, see J. A. Engelhardt, *Trans. VI Comm. Int. Soc. Soil Sci.*, Groningen, 1932, A, 20.

[6] O. Solnar, *Sborn. výzk. úst. zeměd R.Č.S.*, 1927, Sv. 25. For an account of other Czecho-Slovakian work see R. Janota, *Trans. 1st Int. Cong. Soil Sci.*, Washington, 1927, 6th Comm. 726, and F. Gazdik, *ibid.*, 783.

[7] C. Mezger, *Kulturtech.*, 1931, **34**, 118.

imprisoned, would impede the free movement of the rain water. Over the drain, therefore, the water can distribute itself regularly throughout the soil instead of accumulating in one restricted zone near the surface.

Control of Water Supply: (2) Semi-arid Regions.

Fallowing.—In the semi-arid regions the water supply of the soil cannot usually be increased by additions of organic matter: farmyard manure is not available and the ploughing in of green crops is not effective. Summer fallowing is therefore adopted to avoid the loss due to transpiration by the growing crop; it enables the rainfall for two years to be utilised by one crop. This is an old device and it forms the basis of dry farming adopted in regions where the rainfall lies between 15 and 20 inches annually.

The effect of fallowing on the water supply in the soil is well seen in Fig. 63, giving the volumes of air and of water found at Rothamsted on June 27, 1870, during the drought of that year for two adjoining plots of land, one carrying barley and the other fallow. The fallow soil is saturated below 18 inches but water has been withdrawn by the barley down to 54 inches allowing air to enter.[1]

Fallowing has, however, other beneficial effects besides conserving moisture. It causes marked increases in the nitrate content of the soil (p. 238); it keeps down weeds and in humid climates it allows opportunities for bringing the soil into good tilth. It is beneficial both in wet and in dry conditions but much of its advantage is lost if a wet winter intervenes between the fallowing and the sowing.[2]

[1] Note that the soil of the fallow plot happens to have a larger average pore space than the other and hence can hold more water. This possibility is liable to be overlooked when soil moistures are expressed as percentages by weight.

[2] For instances of benefit from fallowing, see *Rothamsted Repts.*, 1927-1928, 1929, 1930 (Table, p. 122) and subsequently; also *Rothamsted Farm Guide* for 1936, wherein see Table, p. 30.

Irrigation.—This subject is so extensive and so specialised that no more than a few references can be given here. Irriga-

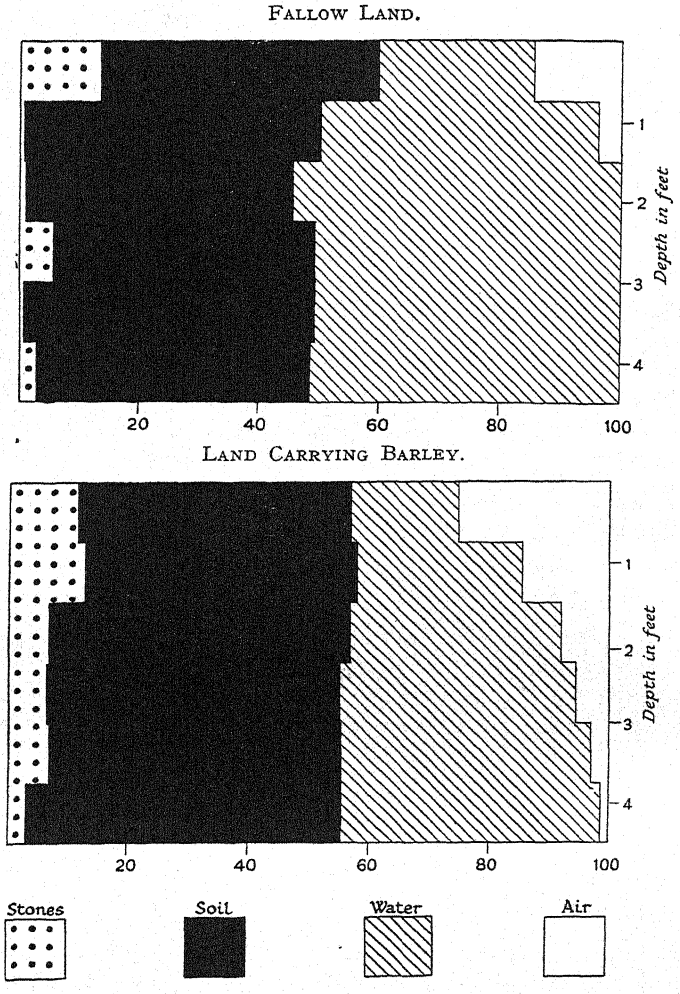


Fig. 63.—Volumes of soil, water, and air at different depths of a fallow and of a cropped soil during a drought at Rothamsted (R. K. Schofield).

tion is simple where the water supply is adequate and free from salt, and the soil is well drained and is also free from salt; it

presents serious difficulties where drainage is defective and where salt is present. The salt problem is discussed on page 322; it should in practice be obviated by making a proper soil survey of the region before irrigation, and by cutting out all areas where it is liable to cause difficulty.

Irrigation troubles are intensified by using too much water, and one of the most important factors in ensuring success is to use only as much as is necessary. Fruit trees (peaches and prunes) may draw their water supply from the top 6 feet of soil but not more; they wilt if this top layer is dry, no matter how much water there may be lower down. Trees can utilise with almost equal ease all the water between the "field capacity" and the wilting point (p. 493); the ideal course therefore is to moisten the soil to its "field capacity" and to the depth penetrated by the roots, but no deeper.[1] This discovery has proved of great importance, and in Viehmeyer's hands has revolutionised irrigation practice in California. Knowing the percentage of water actually present in the soil and the depths of the plant roots, it is easy to calculate the quantity of water per acre that must be added to raise the water content up to the moisture equivalent of the soil which has been determined once for all by the soil survey. Water can be added in excess of this quantity if salts are present in the soil so as to wash them down; in some cases the salts have even been driven 25 feet below the surface.[2] The Californian water engineers have systematised and organised the work admirably, and they have been able to effect great economies in the use of water, and to avoid spoiling of much good land by the application of excess water.

Depth of Soil.

The layer of soil in which plant roots can develop freely is deepened by the following methods:—

[1] A. H. Hendrickson and F. J. Veihmeyer, *Calif. Agric. Expt. Sta. Bull.* No. 573, 1934. For an account of Veihmeyer's work see *Hilgardia*, 1927, **2**, 125; J. P. Conrad and F. J. Veihmeyer, *ibid.*, 1929, 4, 113.

[2] W. P. Kelley, *private communication.*

(1) Drainage, where a water-table limits root development.

(2) Deep ploughing or cultivating to break up a compact layer. This, however, appears to be effective only where organic matter is added to the newly broken lower depth.[1]

(3) The growth of deep rooting crops such as lucerne, the roots of which can both penetrate the subsoil and, on dying, enrich it in organic matter.

(4) Soil can also be deepened by shattering the underlying rock or hard layers with explosives (p. 338). This method is not in general use, though demonstrations of its value have from time to time been given in the United States by the du Pont organisation and others, in South Africa and elsewhere. A notable example is the pulverising of the soft rock in Algeria by nitro-explosives (usually war residues).[2] Holes are bored about 3 feet into the rocky surface; charges are inserted and fired. The rock is broken, and much is pulverised. Large stones can be taken out for building and other purposes. The pulverised material is levelled, and manured with sheep-dung and a complete mixture of artificials. The rain, when it comes, is torrential, but instead of running off as usual and washing away the soil it soaks in and remains stored up for the plants. Potatoes, vines, and fruit trees are grown with great success. Piédallu states that many thousands of trees have been planted and are growing rapidly, and that parks, gardens, and vineyards are thriving, where, but a little while ago, there was nothing but a hot and stony waste.

Permanence of the Soil Layer.

In semi-arid regions the soil remains fairly stable so long as it has some covering of vegetation, but it readily breaks down to dust if the vegetation is removed and the fibrous

[1] S. U. Pickering and E. J. Russell, *J. Agric. Sci.*, 1913, **5**, 483, and much later work: *e.g.* H. G. Sanders, *J. Farm. Cl.*, 1935, Part 5, p. 81.

[2] André Piédallu, *Trans. I Comm. Int. Soc. Soil Sci.*, Versailles, 1934, p. 121.

roots that held the particles together become oxidised. These regions are subject to high winds, and the rainfall when it comes is torrential. Much of the soil is therefore carried away either in the dust storms characteristic of prairie and steppe regions, or in the rush of water caused by the rain. Serious problems thus arise which have been much studied in the United States and in the parts of the British Empire most affected.

In desert conditions the crumbs never formed and the soil layer never was stable: drifting sand has always been a well-recognised feature of the desert. But over large areas in the semi-arid regions of the world there is sufficient vegetation cover in natural conditions to protect the surface soil to a considerable extent against erosion. Unfortunately human exploitation of many of these regions has destroyed this vegetation and so removed the natural protection without supplying any other: in consequence erosion has proceeded rapidly during the last 20 years and vast areas formerly productive have been reduced to sterility.

These methods have been particularly destructive:—

(1) Over-cultivation, especially alternate cultivation and fallowing with no period of rest in grass;

(2) Overstocking: putting too many animals on to the land, so that the vegetation was eaten down too rapidly to allow the cover to be maintained;

(3) Cutting down the forests and making no provision for regeneration or replanting.

All these were practised by the pioneers who went out into the virgin country, and were more concerned with getting rich quickly than with conserving the productiveness of the region.

Over-cultivation.—Great tracts in the United States and in Canada, stable in their natural state, have been rendered liable to erosion by over-cultivation and fallowing. Wheat growing was found to be easy and profitable and economic. Vast areas of prairie land in the United States and Canada that were formerly stable have been rendered sterile by

erosion. So long as the natural vegetation was left undisturbed, the soil retained its crumb structure and was protected against serious loss. But with the rapid extension of wheat cultivation, fostered by the introduction of great cultivating machines, the lands were broken up and alternately cropped and fallowed. For a few years the farmers did well: they cashed the accumulated fertility of the soil. They brought into cultivation all the promising land they could find: trees were cut down, and the natural wind breaks destroyed. Any prairie left uncultivated was heavily grazed during summer and the natural vegetation that had been spared by the plough was destroyed by the animals. Both on the cultivated and on the grazed land, therefore, the organic matter of the soil was rapidly destroyed, and after a time the crumbs fell to dust which readily blew away. The position became aggravated by a succession of years of drought in some of the affected regions: whether this is a consequence or an accidental accompaniment of the removal of vegetation cover is not known. But the effect has been an unpredecented destruction of the soil in the last few years and it is by no means certain that these devastated areas can be restored in our time. The only hope appears to be the establishment of a covering of grass, but how to effect this is at present an unsolved problem.

Over-stocking.—Great damage has been done in the drier regions of South Africa where numbers of farm animals graze on the land, thus reducing the vegetation cover and making tracks down to the drinking places: these form centres of erosion during rainstorms and sooner or later become great gullies or "dongas." Large areas of sloping land have lost their surface soil and are now bare rock.

Erosion has been very serious in the arid grazing regions of Australia. As in other countries the land was over-stocked, and a cycle of dry years intensified the soil-drifting caused by wind. The native vegetation, sparse though it was, afforded protection so long as it was left free to develop, but

usually this did not happen: it was over-grazed and died out leaving the soil without cover. Once soil-drifting begins re-establishment of the native vegetation is difficult: in South Australia, for example, the saltbush *Atriplex vesicarium* grows too slowly to become established, while the various species of *Acacia*, the canegrass (*Spinifex paradoxus*) and other sand-binding plants, have no chance of re-establishment because the seedlings are at once devoured by rabbits. So far no method of treatment has been devised, plants capable of growing sufficiently rapidly not having been found.

Measurements of the amount of rain running off from the soil surface under various conditions of grazing have been made at several stations. In Nebraska, for example, the amounts of "run off" on a 10° slope from 26·9 inches of rainfall during 15 months was 2·5 per cent. from prairie, 9 per cent. from over-grazed pasture, and 15 per cent. from a pasture entirely depleted by close grazing.[1]

Cutting down of Bush and Forest.—Enormous damage has been done by the wholesale clearing of bush and forest in the marginal park or savannah land where trees grew sufficiently well to afford shelter against wind erosion, and to facilitate the removal of rain water by percolation through the soil rather than by running off from the surface.

In Australia serious trouble has been caused by cutting down the forests at the head waters of the Murray River, thereby allowing erosion by rainstorms to proceed. The river has become more liable to flood, and great quantities of silt are carried down: both factors interfere with the irrigation systems. The erosion [2] takes two forms: sheet erosion, which goes on slowly and evenly over a large area, and gulley erosion, which is more localised and washes out the soil into great gulleys or ravines.

[1] J. E. Weaver and W. C. Noll, *Nebr. Univ. Conservation Dept. Bull.*, 11, 1935.

[2] For a good summary see T. Eden, "Soil Erosion," *Imp. Bur. Soi Sci. Tech. Comm.* No. 28, 1933.

The destruction of the forest has not always been brought about by human agency. Some of the moraine country in Poland consists of very light sand which, however, is covered with trees, and these have so reduced the run-off that sufficient water remains stored in the soil to allow a good development of surface vegetation. In consequence the sand is fixed and there is no drifting. Unfortunately, however, in certain areas, a plague of caterpillars defoliated and killed the trees, with the result that the water ran off instead of soaking in, the surface vegetation died, and soil erosion and drifting began. The remedy has been to replant and to take special precautions against the caterpillar.

In one and the same district erosion may take place both by rain and by wind, but there are important differences between the two agencies.

Erosion by Rainstorms.

The important factors at work are :—

(1) The effective rainfall, *i.e.* the rain that runs off carrying soil with it. This is not the same as the total rainfall : at Spur (Texas), for example, where serious erosion losses occur, the average annual rainfall is only 21·7 inches, yet many other places of much higher rainfall do not suffer so much.

(2) The vegetation cover. Erosion under cultivated crops is considerably greater than under forest or undisturbed natural vegetation. W. R. Thompson [1] found at the Pretoria University Farm that land kept fallow and free of vegetation lost eighty times as much soil as land left with its natural vegetation cover. Cultivated crops (*e.g.* maize) did not check erosion : only perennial grass, *e.g.* Rhodes grass, had this effect.[1] Duley and Miller [2] in Missouri find that soils under annual crops suffer from erosion because at some period they

[1] *Univ. Pretoria Publ.*, Ser. 1, No. 29, 1935.

[2] F. L. Duley and M. F. Miller, *Missouri Agric. Expt. Sta. Res. Bull.* No. 63, 1923.

are virtually fallow; in particular soybeans and maize gave little protection, the annual loss of soil averaging 21 and 25 tons per acre as compared with sod and a crop rotation, which lost only 0·25 and 3 tons per acre respectively. American experience shows that grass affords the best cover where it can be established.

The efficiency of a forest cover in preventing erosion is attributed in part to the high water-holding capacity of the litter, though Lowdermilk[1] concludes that the litter fulfils a more important function in preventing the silting up of the soil pore space by the washing down of the finer soil fractions, a process which hinders rapid drainage, and, in consequence, increases run-off water. In Java and in many parts of the British tropical Empire experiments have been made on the tea and rubber plantations on the use of cover crops, altered methods of cultivation and of drainage.

(3) The effect of gradient. The velocity of run-off, and therefore its transporting power, naturally increases with the increase in slope of the land, but the amount of erosion depends also on the type of soil. Clay soils erode more than sandy soils at low gradients, but less at gradients above 15 per cent. H. H. Bennett[2] supposed that soils having SiO_2/R_2O_3 ratios greater than 2 are generally plastic and erosive, while those with lower ratios are friable and non-erosive. Later work has shown, however, that this simple generalisation does not hold widely and at present no clear-cut relation can be given between single properties of the soil and its ease of erosion.[3]

Methods of prevention include the encouragement of ground cover, *e.g.* native vegetation, grass, cover crops of leguminous plants in tropical countries, the levelling of sites,

[1] W. C. Lowdermilk, *J. Forestry*, 1930, **28**, 474; *Agric. Eng.*, 1931, **12**, 107.

[2] *Soil Sci.*, 1926, **21**, 349.

[3] See H. E. Middleton, C. S. Slater and H. G. Byers, *U.S.D.A. Tech. Bull.* No. 316, 1932.

the construction of barriers to break the velocity of run-off water, and in hill districts the terracing or ridging of the land.

The terraces that form so striking a feature of the landscape in Palestine, in Southern France, Italy, and Sicily show that this solution of the problem is an old one. Terracing has been much developed in plantations in the tropical parts of the Empire, and various modifications, such as contour planting, Mangum terraces,[1] are widely adopted.

Erosion also occurs in the orchards of New South Wales, but this is more or less controllable by cultivation. This problem, and the control of gully erosion by dams, has been discussed by Clayton.[2]

Wind Erosion.

This occurs to some extent in all arid and semi-arid regions and it is intensified by the fallowing that usually forms part of the agricultural systems there adopted.

In the United States some 63 million acres have been ruined by wind erosion; so serious is the loss that special experimental stations are set up to deal with it.

Two methods of dealing with the erosion have been used:

(1) The planting of trees to make wind breaks.

(2) Modification in the method of cultivation to minimise its ill-effects.

A colossal wind break, 1000 miles long and 100 miles wide, is to be planted from the Canadian border to the Texas Panhandle at an estimated cost of 75 million dollars.

In Western Canada various modifications of the normal fallowing process are being tried, since wind erosion occurs chiefly on fallow land. These include: (*a*) reducing cultivation to a minimum; (*b*) interspersing fallowed and cultivated strips, set at right angles to the direction of the severest

[1] See A. J. W. Hornby, *Nyasaland Dept. Agric. Bull.* No. 11, 1934, for examples in Nigeria. The various measures adopted in the Colonies are described by F. A. Stockdale, *Emp. Cotton Grow. Rev.*, 1925, **12**, 1.

[2] *Agric. Gaz. N.S.W.*, 1935, pp. 549, 609, 669.

winds ; [1] (*c*) continuous cropping with winter rye followed by oats or spring wheat ; this is risky, however, and may lead to failure in a bad season ; (*d*) substituting tilled crops for fallow. The best crops for this purpose at Swift Current proved to be maize, potatoes, and sunflower, grown in rows so that cultivation implements could keep down the weeds. At Saskatoon oats grown in double rows spaced 3 feet apart responded well to cultivation, and over a period of ten years the succeeding wheat crop, though not as good as after a summer fallow, was nevertheless satisfactory ; the combined value of the wheat and oats was much greater than that of wheat after fallow.[2] Under low rainfall, however, the fallow is better than the tilled crop.

The necessity for reducing cultivation to a minimum, and the conviction that moisture conservation is intimately bound up with weed control, have given a considerable stimulus to the study of this problem. A comprehensive investigation is being made by the Agronomy Departments of the Manitoba Agricultural College and the University of Saskatchewan. Spraying methods of control, especially with 4 per cent. sulphuric acid, appear quite promising.[3]

The method usually adopted is to burn the stubble so as to destroy the weeds : then to harrow in the seed of the next wheat crop. This effectively deals with the weeds, but it hastens the loss of soil organic matter. On *a priori* grounds one would unreservedly condemn this practice, but there is no good experimental evidence that it really is bad. While the fibrous rootlets seem to be useful in building crumbs (p. 517), it is not clear what part the decomposed humus

[1] E. S. Hopkins, S. Barnes, A. E. Palmer, and W. S. Chepil, *Canada Dept. of Agric. Bul.*, 179, 1935 : Hopkins, *Trans. 3rd Int. Cong. Soil Sci.*, 1935, **1**, 403 ; H. C. Moss, *Sci. Agric.*, 1935, **15**, 665.

[2] Manley Champlin, *Proc. World's Grain Exhib. Conf.*, Regina, 1933, **2**, 191.

[3] Papers on Weed Control by G. L. Godell, J. M. Manson, W. S. Chepil, T. K. Pavlychenko, and J. B. Harrington, *ibid.*, 197 *et seq.*

material plays in semi-arid conditions. The Canadian workers, indeed, state that humus facilitates soil drifting.

Characteristics of Common Kinds of Soil.

It is not possible to deal with all the important kinds of soil, but a few of those common in the British Islands are given here as examples of the way in which the soil and vegetation factors interact. The soils concerned are mainly brown earths, or slightly podzolised soils.

Clay Soils.

Clay soils are characterised by the presence of 20 to 60 per cent. of "clay" and considerable quantities of silt and fine silt; in consequence of this excess of fine particles the size of the pores is so diminished that neither air nor water can move freely. Clay soils, therefore, readily become water-logged, and in time of drought may not supply the plant with water sufficiently quickly; in our climate, however, they are usually moist or wet. The high content of clay particles impresses marked colloidal properties: (1) the soil shrinks on drying and forms large gaping cracks which may be several inches wide and more than a foot deep; they may do much damage to plant roots; (2) it absorbs much water, a good deal still being held even when the soil appears to be dry; (3) the water, however, moves only slowly, and it is not uncommon to find a fairly sharp line of demarcation between moist and dry soil, and for land to crack badly within a few feet of a ditch full of water; (4) the soil readily takes part in base exchange and precipitates the phosphate ion from soluble phosphates: it absorbs also many organic substances. During winter, stones, bulbs, and roots are frequently forced out of the ground: this is the result of the high water content of the clay. The expansion that occurs near the freezing-point sets up lateral stresses which buckle the surface layers of the soil, especially where its continuity is broken by the presence

of hard foreign bodies: all these, therefore, are liable to be extruded. The special clay properties are shown, plasticity and adhesiveness when wet, and a tendency to form very hard clods when dry. All these properties are much modified by calcium carbonate and calcium hydroxide; the chalky boulder clay is usually fertile: on the other hand, liquid manure (which contains ammonium bicarbonate) and nitrate of soda (which gives rise to sodium bicarbonate in the soil) may in certain conditions have unfavourable physical effects.

Clay soils have had rather a chequered agricultural history. Originally covered with oak forest and hazel undergrowth they were early reclaimed for agriculture purposes by draining, applications of lime,[1] and, later, of ground bones. Wheat and beans were the great clay crops, and in the early part of the last century, under the combined influence of high prices, large drainage schemes and artificial stimulus to enclosure, great areas came into cultivation, so that now only little unreclaimed clay remains, excepting where the forest was preserved for hunting. Crops grew well but ripened late; a wet harvest was a terrible calamity. Bare fallowing was always necessary once in four years, and any of the intervening years might, if wet, be lost by the difficulty of getting on the land to sow the crop. When the price of wheat fell in the 'eighties of the last century many of these soils went out of cultivation and became covered with a mixed growth of grass and weed, which was grazed by stock and gradually deteriorated as the old drains choked up and the land became more and more water-logged. *Aira cæspitosa*, "bent" grass (*Agrostis vulgaris*), yellow rattle (*Rhinanthus Crista-galli*), and in drier places the quaking grass (*Briza media*) and ox-eye daisy (*Chrysanthemum leucanthemum*) are among the commoner plants on these neglected fields; after continued neglect thorns and other trees spring up and the land reverts to wild woodland; the only relics of the past are the field names and the high ridges or "lands" made

[1] *E.g.* see *The Inrichment of the Weald of Kent*, by R. I., 1625 (attributed in the 1636 and later editions to Gervase Markham).

years ago to facilitate drainage. But much of this rough land has since been improved and converted into useful grass land. Drainage is gradually being attended to, improved implements allow of suitable cultivation, whilst additions of lime and phosphates (as basic slag) have markedly improved the herbage, favouring the development of white clover (*Trifolium repens*), the pasture grasses, also thistles, and crowding out such weed grasses as *Aira cæspitosa*, bent (*Agrostis*) and others. Figs. 64 and 65 show specimens of herbage from some of Robertson's plots at Horndon-on-the-Hill, Essex (London clay). Potassic fertilisers are not usually needed. Only in the dry eastern counties has the old arable cultivation survived.

It is commonly observed that plants growing on clay soils tend to have larger leaves, and to make shorter-jointed growth, than plants on sandy soils. On the other hand, their roots are much less fibrous, much fewer, and tend to be thicker. The mechanical resistance of the clay to the penetration of the root is obviously an important factor in root growth.[1]

In ecological and agricultural surveys it is necessary to distinguish between the silty clays and the true clays. The former owe their heaviness to the presence of much fine silt which differs in colloidal properties from clay (p. 194), and is not flocculated by lime, frost, etc. Indeed, no way is known for ameliorating these soils; they are difficult to drain, and they are generally left as rather poor pasture. The true clays are often indistinguishable on casual inspection, but they behave differently on cultivation and respond to drainage, lime, and good treatment whenever it is deemed worth while to improve them.

[1] For some observations on rhizomes see E. J. Salisbury, *Structure of Woodlands* (*Festschrift Karl Schröter: Geobot. Inst. Rübel* (Zurich), 1925, **3**, 334).

FIG. 65.—Adjoining plot, but treated with Gafsa phosphate, Feb. 27, 1918 Photographed Aug,, 1919.

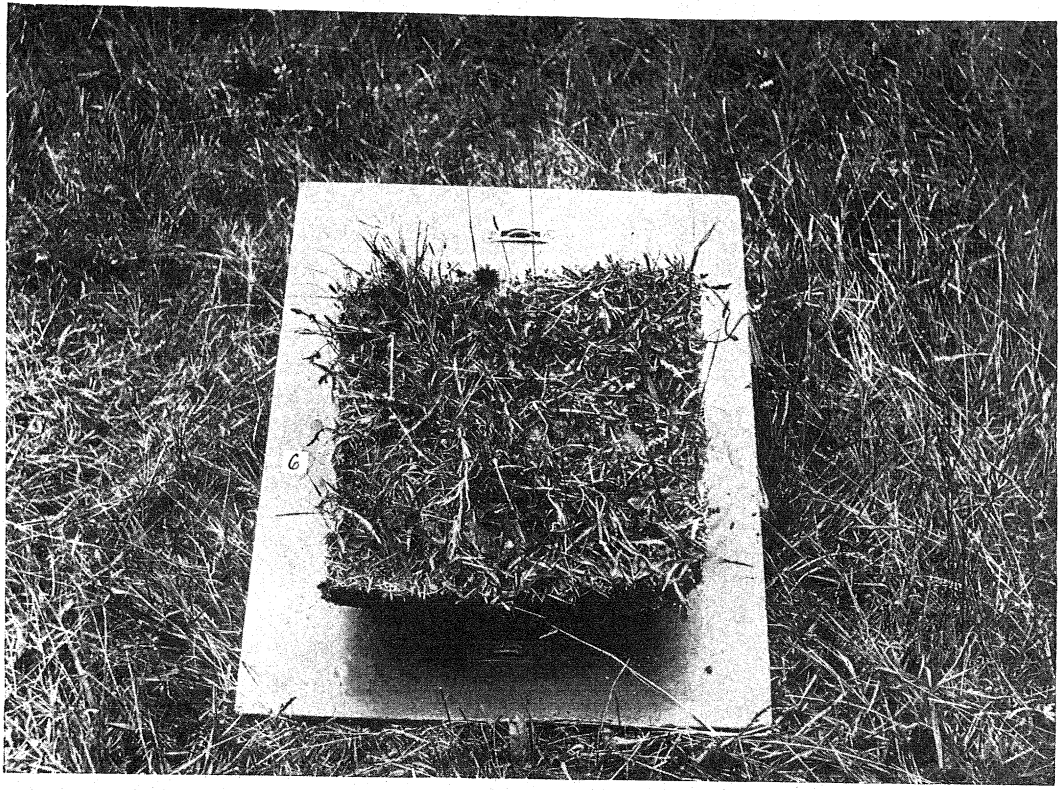


FIG. 64.—Poor grass pasture, untreated plot, Horndon-on-the-hill, Essex (London clay) (G. Scott Robertson).

Sandy Soils.

The vegetation characteristics of these soils are determined by the fact that coarse and fine sand possesses no colloidal properties, no power of base exchange or of precipitating phosphates, and very little power of retaining water. Their pore space structure permits easy movement of water, however. Additions of small amounts of clay or of humus may confer sufficient colloidal and base exchange properties to modify vegetation profoundly.

Sandy soils tend to be dry, loose, and poor in soluble substances—"hungry," the practical man calls them. Their behaviour towards vegetation depends very largely on their position, their depth, and the nature of the subsoil, these being the factors determining the water supply to the plant.

Absence of much clay, presence of much gravel and coarse sand and location on gravel or coarse sand tend to irregularities in the water supply which are fatal to plant growth. The soils are often strongly podzolised, and therefore acid and poor in nutrients with a hard pan in the subsoil. The temperature conditions also fluctuate considerably (p. 507) and this reacts on the vegetation.[1] Extensive areas of such soils exist in the western parts of Norfolk and Suffolk and are left wild as "breckland."[2] Surrey also furnishes examples in the Bagshot and Lower Greensand formations; in places the general dryness is broken by ponds formed by saucer-shaped layers of clay which hold up the water.

Small modifications in the soil composition—an additional percentage of clay and silt, less coarse sand, a somewhat more compact subsoil or frequent rainfall (as, for example, in North Wales) enable these soils to be cultivated. When this is possible they are so attractive to cultivators that none

[1] E. J. Salisbury, *Trans. Norfolk and Norwich. Nat. Soc.*, 1933, **13**, 333.

[2] For ecological studies see E. P. Farrow, *Plant Life on East Anglian Heaths*, Camb. Univ. Press, 1925; and A. S. Watt, *J. Ecol.*, 1936, **24**, 117.

are left uncultivated.[1] They yield early crops of high quality rather than heavy crops, the tendency to drought inducing early maturation, while the absence of stickiness makes cultivation an easy matter at any time. Fruit, nursery stocks, potatoes, and market-garden produce are often raised. Interesting examples can be found in Norfolk where fruit growing, especially of bush fruit, has much increased on the light soils. Sugar beet also is now much grown on these soils, often followed by barley for malting. The winter feeding of sheep on the land was, till recently, the recognised way of fertilising, and swedes were much grown for this purpose, being eaten direct on the field. The leaves and tops of sugar beets are now used instead. Crops must be sown early, or the fertilising material is washed out unused, and the young roots have no time to strike into the subsoil before the surface layer dries out. High farming is the only profitable way of dealing with these soils; any carelessness in cultivation lets in hosts of weeds, such as poppies, knot-weed (*Polygonum aviculare*), spurrey (*Spergula arvensis*), sorrel, horsetail, convolvulus, creeping buttercup, and others. Crops should follow each other in rapid succession, any interval being a period of loss; under good management two or even three market-garden crops can be secured in the year, while in purely farming districts catch crops should always be taken. Calcium carbonate is often needed; potassium salts are beneficial and so for some crops is sodium chloride; nitrates often give remarkable results as also do phosphates on some soils. Only small quantities of manure must be added at a time, as the soil has little retentive power. Above all, no very costly scheme of manuring should be recommended till preliminary trials have shown its profitableness.

In reclaiming or fixing sand dunes the first step is to grow grass, *e.g.* marram grass (*Psamma arenaria* or *Ammophila arundinacea*) which will stabilise the form and then allow a

[1] For fuller information as to the agricultural history of these and other soils, see E. J. Russell, *Fertility of the Soil*, Camb. Univ. Press, 1913.

more varied vegetation, *e.g.* sand binders (*Carex arenaria*, *Festuca rubra*, var. *arenaria*), and winter annuals, to stabilise the surface, ultimately leading to the development of a festuca sward or, in other conditions, to heath and scrub.[1]

Light sandy soils inadequately supplied with water present special difficulties and many of them still remain barren wastes, defying all attempts at reclamation. Two special cases have, however, yielded to treatment:—

(1) When the layer of rock or the pan is only thin and is, in turn, underlain by a rather fine-grained sand, its removal brings about continuity in the soil mass and thus effects a great improvement in the water supply.

(2) Where the gravel or rock is not too near the surface, systematic green manuring with lupins and other crops fertilised by potassium salts and calcium carbonate has often effected sufficient improvement to make cultivation profitable. Examples are afforded by the Schultz-Lupitz estate, Germany,[2] and Dr. Edwards' experiments at Capel St. Andrews, Suffolk, and at Methwold. On such land an industrious cultivator may make a living but not a fortune.

Under favourable conditions recourse may be had to dressings of clay (as in the Fens) or to warping (as in Lincolnshire).

Barren conditions also result when, by reason of a thin parting of clay or its low situation, water cannot run away but accumulates and forms a marsh. Reclamation in such cases is possible as soon as a way out has been found for the water.

Loams.

As the proportion of clay and fine silt in the soil increases and that of coarse material falls off, a gradual change in the character of the soil sets in, till finally, but without any sharp transition, a new type is reached known as a loam. The

[1] See F. W. Oliver and E. J. Salisbury, *Trans. Norfolk and Norwich Nat. Soc.*, 1913, **9**, 485. W. Leach has pointed out the importance of certain mosses as pioneers on unstable soils (*J. Ecol.*, 1931, **19**, 98).

[2] Described by Schultz-Lupitz (1881).

increase of fine material somewhat retards the movements both of air and of water, so that loams are characterised by a more uniform water content throughout the mass than sands. On the other hand, loams show less tendency to become water-logged or to allow plants to become parched in very dry weather than clays. The soil decompositions proceed normally, rapidly producing plant food, with little tendency to "sour" or other abnormal conditions so long as sufficient calcium carbonate is present. In consequence, most plants will grow on loams, even some of those supposed to be specially associated with some other soil type. Thus, where a chalk and a loam soil meet, it is not uncommon to find the chalk plants, *e.g.* traveller's joy (*Clematis vitalba*), guelder rose, etc., wandering on to the loam, and it is much more difficult to find the line of separation of the soils than where the chalk abuts on to a sand or a clay. For the same reason loams allow of very wide choice in the systems of husbandry, and, as they become very fertile under good management, they are usually in this country all cultivated. Closer observation over a limited area shows, however, that a given class of loam is more suited to one crop than to another; the ecologist recognises differences in the sub-associations or facies, and the practical man will distinguish between a potato soil, a barley soil, a wheat soil, etc.: distinctions due, no doubt, to water and air relationships, and arising from differences in the compound particles. These have not been much studied in the field, but the ultimate particles have been determined by mechanical analysis: illustrations are given in Table 108.

Low amounts of clay and fine silt, and high amounts of coarse sand, whenever the clay begins to approach 12 per cent., characterise the potato soils; these are the most porous of the series, allowing free drainage and aeration. Barley tolerates heavier and shallower soils. Fruit and hops both require deep soils, and seem to find their most favourable circumstances only in a restricted class of soils: the fruit soils generally contain rather more sand and less silt than the hop

TABLE 108.—MECHANICAL ANALYSES OF SOILS WELL SUITED TO CERTAIN CROPS IN KENT, SURREY AND SUSSEX; LIMITS OF VARIATION. A. D. HALL AND E. J. RUSSELL.[1]

	Potatoes.	Barley.	Fruit.	Hops.	Wheat.	Waste Land.
Fine gravel	0·1-3	0·2-2·5	0·3-2·3	0·3-2·3	0·4-6	1-7
Coarse sand	2-47	1-53	0·8-9·5	0·7-9·5	0-13	16-69
Fine sand	23-68	20-45	30-55	25-39	15-31	18-64
Silt .	3·5-21·4	5-33	13-44	20-45	11-35·5	2-7
Fine silt .	5-9	3·5-16·4	6-11	6-11	9·5-24	2
Clay .	5·5-12·6	4-19	10·5-14·6	11·5-15	13-24	1 or less

soils. But the fruits differ among themselves; the best nursery stock is raised on soils of the potato class, where the conditions are for some unknown reason very favourable to fibrous root development; strawberries prefer the lighter and apples the heavier kinds of fruit soil.[2] Even different varieties of the same plant grow better on one class of soil than on another: the finest varieties of hops are found only on the typical hop soils, and have to be replaced by coarser varieties directly it is desired to grow hops on heavier soils. Preferences for certain soil conditions are also shown by varieties of the common crops, oats, barley, wheat, etc.; unfortunately these can only be discovered by direct field trials, and even then the results hold only so long as similar conditions prevail and may often be reversed in a different climate or season.

Wheat grown on entirely suitable loam tillers well, produces stiff straw and ears copiously set with corn, so that a crop of 50 or 60 bushels per acre may be raised without difficulty; on soil rather different in type, and especially under somewhat different climatic conditions, only 30 or 40 bushels can be raised, because the ears are less thickly set and the straw is too weak to carry a heavier crop, becoming "laid" directly an attempt is made to increase production

[1] *Agriculture and Soils of Kent, Surrey and Sussex*, Board of Agriculture, 1911.

[2] For a study of fruit soils see C. Wright and J. F. Ward, *Min. Agric. Res. Monograph* No. 6, 1929.

by increased manuring. Whether some unknown nutrient is absent from these soils, or whether the adjustment of the air and water supply is wrong, is not known; but the limitation of yield arising from this unsuitability of soil conditions is a serious agricultural problem.

Not only is the amount of growth altered, but the composition and character of the plant. Barley grown on some soils produces much better malt than on others.[1] Potatoes grown in the Dunbar district are remarkable for their quality; they will stand boiling and subsequent warming-up without going black. The same varieties of potatoes grown in the same way in the Fens blacken badly under the same treatment, and consequently obtain a lower price in the market.

Grass is considerably affected by variations in soil conditions.

In Romney Marsh pastures commonly occur carrying a vegetation of rye grass and white clover, with crested dog's-tail and *Agrostis*, easily capable of fattening sheep in summer without any other food. All round these pastures are others, with *the same type of vegetation*, but the plants grow more slowly, produce more stem and less leaf, are less nutritious and *incapable of fattening sheep*. The soils are identical in mechanical analysis and in general water and temperature relationships, although certain differences have been detected.[2] Some of the grass grown on Lower Lias pastures in Somersetshire and Warwickshire causes acute diarrhœa ("scouring") in cattle, whilst grass on adjoining alluvial pastures does not.[3] Other harmful effects are periodically recorded. Reference has already been made to the injurious effects of lack of phosphate and of acidity on grazing land (pp. 82, 543).

The agricultural treatment of loams, as already indicated, admits of considerable variety. The old plan was to apply

[1] For full discussion see E. J. Russell and L. R. Bishop, *J. Inst. Brew.*, 1933, **39**, 287.

[2] A. D. Hall and E. J. Russell, *J. Agric. Sci.*, 1912, **4**, 339.

[3] C. T. Gimingham, *J. Bd. Agric.*, 1910, **17**, 529, and *J. Agric. Sci.*, 1914, **6**, 328.

a good dressing of dung every fourth year and a smaller intermediate dressing; clover was also grown every fourth year, and, on light loams, the root crop was eaten by animals on the land. At long intervals lime was applied and sometimes bones. The modern movement is towards specialisation, each man producing the crops he can best grow and managing them in the way he finds most profitable, but the system usually involves feeding a good deal of imported food to sheep and cattle, either on the land, or in yards, and utilising the excretions as manure, buying nitrate of soda, sulphate of ammonia, and manufacturers' waste products (generally those derived from imported animal or vegetable products) to supply more nitrogen, and buying also imported phosphates and potassium salts. Thus the fertility of highly-farmed countries like England tends to increase at the expense of new countries that export large amounts of animal and vegetable produce. But the transfer is prodigiously wasteful; enormous losses arise in virgin countries through continuous cultivation (p. 378), and at this end in making dung, and especially through our methods of sewage disposal. It seems inevitable that these losses must make themselves felt some day, unless the movement for the conservation of natural resources ever becomes a potent factor in international life.

Calcareous Soils.

On these soils calcium carbonate is the controlling factor in determining the soil properties. The conditions here seem to be extraordinarily well suited to plant and animal life. Bacteria are numerous and active, rapidly oxidising organic matter. Hosts of animals, wireworms, earthworms, and others live in the grass land, and even get into the arable land, honeycombing the soil with their passages, puffing it up or "lightening" it considerably, and encouraging the multiplication of moles. Rabbits abound in dry places. Vegetation is restricted on thin exposed soils, but becomes

astonishingly varied where there is sufficient depth of soil and shelter to maintain an adequate water supply. Ash is the characteristic tree in the north and west, and beech in the south of England, and there is a great profusion of shrubs—buckthorn, spindle, guelder rose, dogwood, hawthorn, hazel, maple ; and especially of flowering plants—scabious (S. *Columbaria*), the bedstraws, vetches, ragwort, yellow wort (*Chlora perfoliata*), salad burnet (*Poterium sanguisorba*), lady's fingers (*Anthyllis*), *Linum catharticum*, *Lotus corniculatus*, *Cirsium acaule*, *Helianthemum vulgare*. Of the grasses on the chalk downs and pastures the commonest include *Festuca ovina* and *rubra*, *Avena pratensis*, *Trisetum flavescens*, *Briza media*, *Bromus erectus*, *Kœleria gracilis* (*cristata*). *Carex flacca* (*glauca*) is also common.[1]

Still more remarkable than the existence of a chalk or " calcicolous " flora is that fact that a few plants, the so-called calcifuges, do not occur : they are found only in pockets of acid soil. Some are always calcifugous, *e.g. Calluna* (p. 546), and rhododendrons ; in general, however, neither the calcicolous nor the calcifugous habits are constant properties of the plant, but are affected by climate or other external conditions, and particularly by the competition of other plants. W. E. Brenchley finds that the calcifuges of the West of England are not all calcifuges in the drier eastern counties,[2] and that many of the calcifuges of the dry eastern counties grow freely on the chalk in the moister west. This seems to be general : J. A. Wheldon and A. Wilson [3] found that many more species of plants on calcareous soils in the humid climate of West Lancashire than on corresponding soils in the drier climate of Yorkshire. Conversely, E. J. Salisbury and also W. E. Brenchley show that plants which are calcicolous in moist

[1] The vegetation of English chalk has been studied in detail by A. G. Tansley and R. S. Adamson, *J. Ecol.*, 1922, **9**, 114 ; 1923, **10**, 168, and 1925, **13**, 177.

[2] *Ann. Bot.*, 1912, **26**, 95.

[3] *Flora of West Lancashire*, Eastbourne, 1907.

climates are indifferent in the drier regions, and are not confined to chalks.

The earlier investigators did not distinguish between the effects due to acidity and those due to deficiency of calcium, but this is done in all good modern work. In their studies of the Tatra region (Polish Carpathians) J. Włodek, E. Ralski, and M. Wodzicka [1] distinguish three groups of plants in relation to calcium supply and acidity: (1) those widely tolerant of soil reaction but needing a high concentration of calcium ions in the rhizosphere, *e.g. Festuca versicolor; F. Carpartica;* (2) those requiring almost neutral or faintly alkaline soil reaction, and a high concentration of calcium ions, *e.g. Thalictrum minus, Carex Tatrorum;* (3) those requiring almost neutral or faintly alkaline soil reaction but not necessarily a high concentration of calcium ions, *e.g. Saxifraga perdurans* and perhaps also *Artemisia petrosa.*

B. L. T. De Silva [2] shows that, in the South of England, the distribution of the calcifuges generally follows the soil reaction, while that of the calcicoles is more closely connected with the amount of exchangeable calcium in the soil: calcicoles will grow on acid soils if sufficient exchangeable calcium is present, while calcifuges will tolerate exchangeable calcium so long as the soil reaction is acid.

When there is no competition from other plants many so-called calcifuges will grow in presence of calcium carbonate. In a prolonged investigation near Karlstadt, Kraus (1911) found no plant rigidly restricted in its calcium carbonate relationships, although some preferred more, *e.g. Festuca glauca, Teucrium montanum,* and *Melica ciliata,* while others preferred less, *e.g. Brachypodium pinnatum, Kœleria cristata,* and *Hieracium pilosella.* True chalk plants were found on the adjoining sand, especially when some calcium carbonate was present, although the true sand plants did not wander on to the chalk. In such cases of displacement or " heterotopy "

[1] *Bull. Int. Acad. Polon.*, 1933, Ser. B, 1, 210.
[2] *J. Ecol.*, 1934, **22**, 532.

it was shown that the general physical conditions of the two locations were similar in spite of their wide difference in chemical composition. Kraus, therefore, argues that the true chalk plants inhabit chalk soils not because they need much calcium carbonate, but because they find there the general physical and chemical conditions they require. Salisbury expands this view and shows that plants come on to the chalk for two reasons: for the general physical conditions, aeration and moderate water supply; and for chemical reasons, especially the absence of acidity and the abundant supply of calcium. But if these conditions are satisfied on other soils they will grow there quite well. Thus the beech thrives best in a somewhat dry, well-aerated soil. In the south-east of England it finds these conditions as a rule mainly on the chalk soils. But elsewhere it finds them on other soils so that the plant is not calcicolous. On the other hand, *Solanum dulcamara*, *Fraxinus excelsior*, *Cornus sanguinea* and others come on to the chalk to avoid acidity. They tolerate wet conditions quite well and in acid areas they occur in the wet places: in like manner a non-acid type of vegetation is often found in these parts of acid woodlands liable to flood.[1]

Other plants which are not definitely calcicolous or calcifugous are liable to nutritional disturbances, particularly to chlorosis, if the proportion of calcium carbonate in the soil becomes too high (p. 103).

The agricultural value of chalk soils depends very largely on their depth, and is much greater in valleys, where the soil and water collect, than on the higher ground, where the soil is thinner. The two defects most in need of remedy are the lack of organic matter and the tendency to become light: these are met by additions of dung or other organic manures, by rolling and cultivating with heavy instruments, and above all by feeding animals on the land with the crops actually growing there and with purchased food, a process known as "folding."

[1] The effects of soil acidity are less pronounced in wet than in dry conditions; see p. 538.

Both the treading and the manuring are advantageous.[1] Sheep are by far the most suitable animals, and they form the centre round which the arable husbandry of chalk districts has developed; indeed, so important are they that each chalk region has evolved its own breed of sheep—South Downs, Hampshires, etc. As fertilisers, potassic manures, especially kainit, are generally profitable; superphosphate is needed for turnips, and in wet districts basic slag is useful on the grass land. Skilful cultivation is always necessary, or the soil dries into hard, steely lumps that will not break down. And, lastly, the pre-eminent suitability of the chalk to plant and animal life has its disadvantages; no soils are more prone to carry weeds, turnip "fly" or wireworm. Drastic changes are now occurring in the management of the chalk, however: arable land sheep are proving uneconomical and grass land sheep and dairy cattle are displacing them. Skilful management is the keynote of success, and it generally obtains, for bad farmers do not usually survive many seasons.

The fact that a calcareous rock lies beneath is no proof that the soil itself is calcareous: on the contrary, the soil may often contain practically no calcium carbonate, either because it has become decalcified by rain, or because it really represents some deposit of wholly extraneous origin.

Humus Soils.

Humus soils are divided into two groups:—

(1) Acid humus, or raw humus: moorland soils.

(2) "Neutral" humus, or mull: fen soils.

The agricultural and ecological characteristics of peat moors are:—

(1) Wetness.

(2) Deficient aeration: the vegetation has to be specially adapted to meet this.

(3) Acidity.

(4) Low content of calcium and other bases.

[1] *Rothamsted Conference Repts.*, No. 12, 1931.

(5) Absence of nitrate and low power of nitrification[1] so that plants must usually obtain their nitrogen from ammonia or other sources.

Numerous schemes have been projected for utilising the great peat areas, and they may roughly be grouped into two classes :—

(1) Ameliorating substances (such as lime, artificial manures, etc.) are added, and the peat is cultivated as if it were normal soil. This is possible only when the deposits do not lie too high.

(2) The peat is removed and sold, and if the climate allows the underlying formation is—

(*a*) Ploughed up, if it is clay or sand.

(*b*) Covered with town refuse and then cultivated, as at Chat Moss.

(*c*) Warped, *i.e.* systematically flooded with tidal water carrying silt till several feet of soil have been formed ; this is only possible in a few areas, *e.g.* in Lincolnshire, lying below high-water level.

Investigations of methods of cultivating high moor (*Hochmoor*) soils, continuing over many years, have been made at the Bremen Moorkultur-Anstalt, first under B. Tacke and now under Fr. Brüne,[2] and of low moor (*Niederungsmoor*) at Jönköping in Sweden, first by von Feilitzen, now by G. Rappe ; recently also stations have been started at Neuhammerstein in Pomerania, and in the island of Lewis by W. G. Ogg and the staff of the Macaulay Institute for Soil Research.

The alternative method of removing the peat and using it for fuel or other purposes, then cultivating the underlying soil, is adopted both in England and in Holland.

At Groningen, where reclamation is still going on, the peat

[1] For studies of nitrification and other bacterial actions in moorland soils, see E. Gully, *Landw. Jahrb. Bayern*, 1916, 6, 1-81 ; Th. Arndt, *Centr. Bakt. Par.* II, 1919, 49, 1-51.

[2] The results are published by *Verein für Forderung der Moorkultur* and in *Landw. Jahrb.*

is mainly composed of *Sphagnum* and *Eriophorum vaginatum*. The first stage is as always the making of canals and ditches as the basis of the drainage system. The later stages are based on the fact that the newly-formed peat of the upper layer is suitable for cultivation, but not for fuel, because it burns too quickly (it is used for tinder or as litter), while the old peat of the lower layer is unsuitable for cultivation because its high content of colloidal matter makes it too retentive of water when wet and very dusty when dry. The process consists therefore in taking away the old underlying peat but retaining the more recent top layer. In the first instance the whole of the peat is taken right away for use as fuel or other purposes, and the top layer is put back again : if as much as 80 cm. or 1 m. can be obtained so much the better. The surface is then levelled and pieces of old trees or turf removed if possible. Then on top of this is put a layer of sand about 8 cm. thick taken out from the ditches. The cultivating implements go through to mix this sand with about 4 cm. of the peat. In the old days it was customary to give heavy dressings of town refuse : 20 to 30 tons per acre in the first year with smaller dressings in the second. Now, however, artificials are used exclusively. Potatoes are grown as a first crop and given heavy dressings of fertilisers,[1] with a small dose of copper sulphate if necessary (p. 108). Then follows rye. Then lime is added and oats are grown, undersown with clover, followed by sugar beet and wheat.

Fen.—The best example in Great Britain is found in the Fens, a low-lying area adjoining the river Ouse and its tributaries in Norfolk, Cambridgeshire, etc. These soils are rich in nitrogen, no less than 3 per cent. being sometimes found ; they also contain much exchangeable calcium and the drainage waters are neutral. The vegetation therefore includes calcicolous plants as well as those indifferent to calcium

[1] The amounts given per hectare are 120 to 140 kg. each of K_2O (as sulphate or muriate) and of PO_4 (as superphosphate), and 150 to 170 kg. of nitrate of soda.

supply (*Phragmites*, *Cladium*, *Scirpus*, and *Carex* in England), and crops do not respond to lime.

The region was not much in cultivation till the great reclamation schemes of the seventeenth century, when Vermuyden, the engineer, and the Duke of Bedford and other enterprising capitalists took the matter in hand and erected the great dykes, drains, and pumps that alone keep the land dry and usable.

When drained, these soils proved extraordinary fertile, and all would now be in cultivation but for the deliberate saving of Wicken Fen as a wild life sanctuary.[1] Their high fertility is due to—

(1) Their high content of organic matter and of bases.

(2) The absence of acidity.

(3) The presence of a water table near the surface, yet sufficiently far down to allow of copious root aeration.

Farmers distinguish two types of fen: the clay fen on the western side and the sandy fen on the eastern side of the region; the difference lies probably in the subjacent material, there being little evidence of any difference in the actual fen. The Kimmeridge clay on the west lies about 5 feet below, but occasionally it comes above the surface and forms the rising ground on which alone dwellings could be built before the reclamation—the "eys" or islands of the old days. On the east the fen is underlain by sand.

The most common crops are wheat, potatoes, the introduction of which some thirty years ago completely revolutionised fen husbandry, and sugar beet, which has recently effected another great change. In smaller quantities mangolds, celery, mustard seed, cole seed, rye grass seed, buckwheat, and other seeds are grown. Corn crops, however, do not finish well: they start well but do not "corn out." Where clay lies underneath, a complete remedy lies in bringing up the clay and spreading it: this is done about once in

[1] Ecological studies of Wicken Fen are in progress and are reported in the *Journal of Ecology*. See, for example, H. Godwin, *J. Ecol.*, 1936, **24**, 82.

twenty years. The soils shrink very much on drying, forming large cracks dangerous to animals and sometimes destructive to cart wheels. Oxidation is continually proceeding at a rapid rate, and within living memory the fen has shrunk several feet: in many cases it only has another 5 or 6 feet to fall before disappearing altogether (p. 211).

Fen soils do not require lime or nitrogenous manures, or as a rule potash, but they respond in a marked degree to superphosphate.[1] Summer fallow has a bad effect on them.

In practice, the clay fen soils after their periodical claying receive nothing but superphosphate: they are extraordinarily fertile, commonly yielding 10 tons of potatoes, 90 bushels of oats, and 56 bushels of wheat per acre. The sandy fen soils are less fertile, because they cannot be clayed except at great expense: the chief need again is for phosphate, but potassium also is wanted.

The "muck land" of the United States appears to be of the same type: it is underlain by shell deposits containing lime, and no structure can be detected in the organic matter: it responds, however, to lime and potassic fertilisers.

Soil Mapping.

Two groups of soil surveys have been made. The general survey aims at recording the major types and showing how their distribution is related to the climatic, geological, topographical, vegetation, and other conditions over the area concerned. A soil map of Europe has been constructed during the last twenty years by Professor Stremme, of Danzig, with the collaboration of many soil workers in different countries. An elaborate series of maps of the soil zones of Russia is being built up under the supervision of Professors Polynov, Prasolov and their colleagues of the Dokuchaev Institute, Moscow (formerly at Leningrad), a soil map of Australia has been prepared by J. A. Prescott, and one of East Africa under

[1] See *Rothamsted Rept.*, 1933, p. 23.

the editorship of G. Milne of Amani. These surveys are of great scientific interest in providing data for the study of soil morphology, and they are of practical value in showing the regions within which particular kinds of soil may be expected.

For the purposes of the practical farmer the scale of these maps is, however, too small. Much more detailed surveys are needed for agricultural advisory purposes, and these have been going on in this country for the past forty years. In the earlier ones by Hall and Russell of Kent, Surrey and Sussex, and by C. M. Luxmoore of Dorset, the soils were grouped according to geological origin, with sub-divisions based on mechanical analysis. This basis was inadequate for the older geological formations, and the later surveys have more usually been based on the properties of the soil profile. Unfortunately the surveys have not as a rule been published, and the results are therefore not generally available, so that much valuable work lies hidden.

Meanwhile the Land Utilisation Survey of Great Britain is proceeding and a number of maps have already been published.[1]

[1] The maps are published by the Ordnance Survey. The reports are issued as parts of *The Land of Britain, Report of the Land Utilisation Survey of Britain*, edited by L. Dudley Stamp (London School of Economics).

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